A KNOWLEDGE-BASED BIM EXCHANGE MODEL FOR CONSTRUCTABILITY ASSESSMENT OF COMMERCIAL BUILDING DESIGNS

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A KNOWLEDGE-BASED BIM EXCHANGE MODEL FOR CONSTRUCTABILITY ASSESSMENT OF COMMERCIAL BUILDING DESIGNS

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Dedicated to my love, classmate, colleague, and spouse
Mehdi Nourbakhsh

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LIST OF SYMBOLS AND ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
AEC	Architecture, Engineering, and Construction
AISC	American Institute of Steel Construction
BAMie	Building Automation Modeling information exchange
BCAEM	BIM-based Constructability Exchange Model
BIM	Building Information Modeling
BPMN	Business Process Modeling Notation
BLIS	Building Lifecycle Interoperable Software
CII	Construction Industry Institute
COBie	Construction Operations Building Information Exchange
CSI	Construction Specification Institute
EM	Exchange Model
HVACie	Heating Ventilation and Air Conditioning information exchange
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IDM	Information Delivery Manual
MVD	Model View Definitions
NBIMS	National Building Information Modeling Standard
PCI	Precast/Prestressed Concrete Institute
RFI	Requests for Information
WALLie	Wall Information Exchange

SUMMARY

At the early design stage of construction projects, designers often rely on general rules of thumb to make critical decisions about the geometry, construction systems, and materials used in their designs without fully evaluating the applicable construction requirements and constraints. However, ease of construction, or constructability, is a critical factor that is best examined at the early stage of construction projects when designs are the most amenable to change. Currently, reviewing designs' constructability requires that designers spend a significant amount of time manually extracting constructability data from building models. Data extraction for constructability presents a challenging task, especially in large and complex projects, in which designers may neglect important data pertinent to, or extract unnecessary data from, their designs. The absence of a quantitative constructability model in the United States and a schema for extracting the necessary data for an automated constructability assessment of building designs motivated this study to develop a building information modeling-based constructability assessment exchange model. Through a comprehensive review of the literature, seventy-nine constructability attributes were first identified, which were then categorized into six groups using factor analysis based on 298 responses received from a questionnaire-based survey of industry professionals. Then using pairwise comparisons between constructability factors and common building systems used in the United States, a constructability assessment model was developed with the knowledge obtained from construction experts. Next, this study created a constructability exchange model (EM) using the United States National Building Information Modeling Standard™ approach to automate the data extraction required for the constructability assessment. The proposed EM identifies a reusable and

consistent data set (e.g., geometry, object structures, relations, and properties) required for constructability assessment of building designs. The constructability EM was validated through an experiment based approach to examine if the model would help designers explore the constructability of designs in less time, assess the constructability of designs more accurately, and formalize the method of constructability assessment. We also validated the constructability EM using the IfcDoc application, so software vendors can use the EM to examine if their importers and exporters comply with the terminology and rule sets it defines. Moreover, domain experts can use it to validate their models to ensure they have all the required information for assessing constructability. Using the proposed constructability assessment model, designers can identify the tradeoffs involved in the constructability of various design alternatives and make informed decisions about any proposed changes. The constructability EM provides formal classifications of construction information that, when implemented, automates the repeated and time-consuming task of constructability assessment of designs.

CHAPTER 1

INTRODUCTION

This chapter presents the motivation and problem definition, gap of knowledge, objectives, scope, and outline of this research.

Motivation and Problem Definition

In most construction projects, design documents produced by designers do not satisfy the construction requirements favored by contractors. One reason is that contractors tend to prefer a design with less construction complexity and cost, while designers focus on the aesthetics, functionality, and efficiency of the design (Fischer, 1991b). In addition, because designers and contractors usually do not work together from the beginning of a project, designers may not be aware of all the applicable construction constraints and requirements at the early design stage, resulting in designs that are either incomplete or difficult to build. Such uncoordinated and incomplete designs cause design revisions, numerous requests for information (RFIs), disputes, delays, and extra cost to complete the project (Ruby, 2008). However, designers can minimize or even eliminate the potential risk of project delays, change orders, and extra costs (McDowall, 2008), if they consider the completeness of a design and its construction requirements at the early stages of design, instead of relying on contractors to review their design, find errors, and ensure that the design is complete.

When designers fail to base critical decisions on construction requirements and constraints, they soon realize that their designs result in problems in construction (Fischer, 1991b). Because changes during the construction phase of projects may be extremely difficult to accommodate and can involve substantial cost, contractors often find themselves recreating an easier-to-build project, a process that may prove both costly and time-consuming (Figure 1).

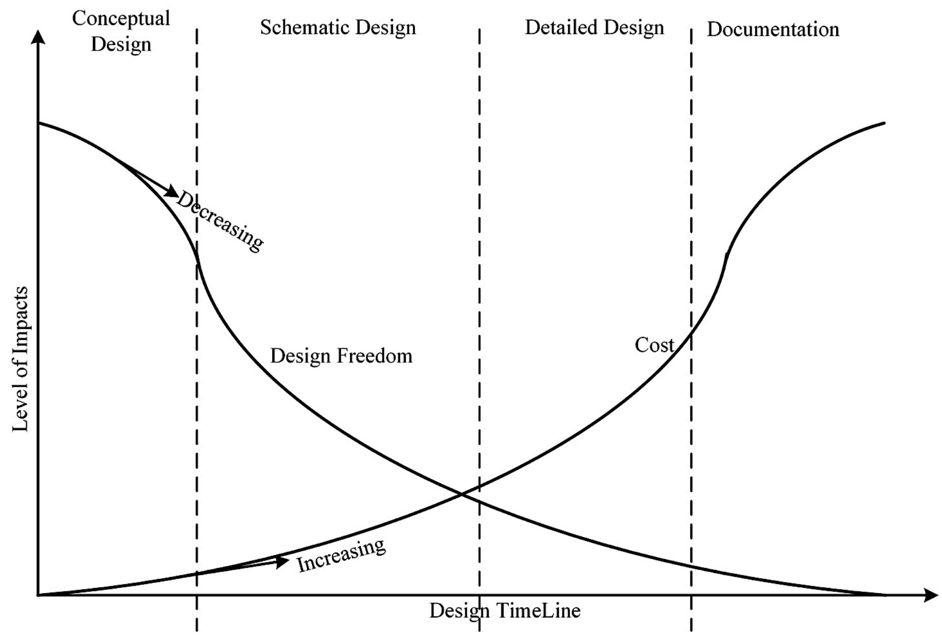


Figure 1: Impact of design freedom and expenditure in a design process, adopted from (MacLeamy, 2004)

Constructability Knowledge

At the early design stage of a construction project, designers make critical decisions about the layout, geometry, dimensions, structural systems, building materials, and various components of a building system, which ultimately determine the ease with which a design can be built at the construction stage. Lack of construction knowledge and reliance on general rules of thumbs for making such decisions can increase the complexity of a design and the need for change orders, often necessitating a redesign. In contrast, effective decisions made at the design stage can decrease costs, increase constructability, and enhance quality and building performance (Flager and Haymaker, 2007, Rodrigo Mora et al., 2006). Therefore, the integration of design and construction at the early design stage can fill the gap between designers and construction managers and result in lower-cost designs (Fischer, 1991b).

Integrating construction knowledge into design is crucial, particularly in light of the current demand for skilled workers in the United States (U.S.) commercial construction sector (Albattah et al., 2015, Dai et al., 2009), where 74 percent of companies are hard pressed to find skilled labor (Gonzales, 2013). Other countries such as Singapore have also had trouble meeting the demand for construction labor and have enacted legislation to reduce reliance on workers by integrating construction knowledge into the initial design using a constructability scoring system (BCA, 2014). Thus, the question arises as to how designers, with their limited knowledge of construction, can better incorporate construction requirements and constraints to produce easy-to-build designs.

To improve the constructability of design and to increase designers' knowledge of construction, researchers have introduced the concept of constructability, defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objectives" (CII, 1986). Applying constructability concepts at the early stage of construction projects reduces the cost of design and construction and improves project planning and scheduling, design coordination (Ruby, 2008), and worker productivity (BCA, 2014). Constructability differs from value engineering in terms of time and scope. Constructability happens before the detailed design phase and fosters more design freedom, but value engineering primarily happens during the construction documentation phase, when most design decisions have been already made (CII, 1986). Nevertheless, a value engineering review may contain some constructability concepts, such as site constraints, fabrication and erection processes, and framing and connection details (Ruby, 2008). Chapter 2 describes constructability and its relevant factors in more details.

BIM-based Constructability Assessment

Since designers create and deliver building models to contractors, they need to know the type of information they should extract from building information modeling (BIM) models to assess the constructability of their designs. Using these information templates, known as exchange models (EMs), designers can detect what is missing and determine what needs to be included in a design to enhance its constructability. To improve methods of data transfer and sharing in the design process and to increase the usability of data for different workflows, the National Building Information Modeling Standard-United States (NBIMS) has generated several BIM standard projects. These standards include process models that identify information exchange among various disciplines during the design and construction processes. Software developers use this information and the process models for developing shareable model views for visualization and coordination of production. For instance, NBIMS developed American Institute of Steel Construction (AISC) EMs for multiple tasks and phases of steel projects such as the structural contract EM or the final steel detailing EM, which supports exchanging data from steel detailing software to CNC fabrications (DBL, 2013). Despite these current efforts, no EMs have been developed for the constructability assessment of building designs. Moreover, no database exists to capture and organize design information for constructability enhancement in a manner that can be reused and retrieved later. The lack of an efficient and accurate set of standard EMs limits access to a reliable information exchange for a BIM-based constructability assessment of building designs. These shortcomings are reflected in a low adoption rate of BIM in the constructability assessment of building designs, which affects scheduling, budgeting, and cost-estimating capabilities.

Research Objectives

The aim of this study was to generate a reusable and retrievable knowledge-based EM for BIM-based constructability assessment to facilitate efficient data extraction and exchanges from design models. Such an EM enables designers to explore commercial building design alternatives at the early design phase and to select the easiest design to build. To achieve this goal, this study established the following objectives:

1) to identify and prioritize the essential constructability factors of building designs;
2) to formulate a model for constructability assessment of building designs;
3) to create a BIM-based EM for a seamless constructability assessment of designs; and
4) to examine the application of the BIM-based constructability assessment EM (BCAEM).

To address the shortcomings in the current design process outlined above, this research identified the required constructability knowledge and constraints to be integrated into building designs at the early design stage. It also devised an EM to identify and retrieve the minimum set of information items required for the constructability assessment of building designs that provide formal definitions of a BIM-based constructability assessment EM and streamline the current design process into a more consistent and modular process. Moreover, the EM will provide designers a complete set of information exchanges necessary to implement a BIM-based constructability assessment of building designs. The EM allows more system integration among disciplines, as well as integration of the BIM-based constructability concept at the early design stage. It also enables all disciplines to contribute essential details and conditions to the decision-making process and to achieve more accurate results.

Research Questions

This study attempts to answer the following questions:

<u>*Constructability Assessment Model:*</u>

1. *What are the required factors for the constructability assessment of building designs?*

No set of data currently exists to provide the required information items for the constructability assessment of building designs within the U. S. construction industry. Designers still do not know essential constructability factors affecting building designs. The goal of this research question was to specify the information designers need for the constructability assessment of building designs and to provide a basis for the content of an EM.

2. *What is the relative importance of these factors on the constructability of building designs?*

   Certain constructability factors may be extremely important to facilitate the construction of building designs, while other factors may prove less important. Identifying the relative importance of these factors can help designers understand the contribution of the factors in creating more constructible designs.

Constructability Exchange Model:

3. *Which information is required for a seamless BIM-based constructability assessment of building designs?*

   No BIM-based constructability assessment model exists to support all major exchanges dealing with the constructability requirements of building designs. The absence of such a BIM-based EM leaves designers no choice but to review all constructability constraints and requirements manually, a time-consuming and error-prone process. The goal of this research question was to devise a BIM-based EM mapped into IFC schema based on the functional specifications identified in the first and second questions. This model will identify and apply the minimum set of information items required for the constructability assessment of building designs.

<u>*Validations:*</u>

4. *What is the impact of BIM-based constructability assessment exchange model on the constructability assessment of designs?*

   The literature recognizes lack of reusability as one of the limitations of constructability assessment models. However, this research question examined whether the integration of the constructability knowledge into BIM can help designers more efficiently measure the constructability of designs involving different structures and construction systems.

Research Scope

The goal of this study was to generate a reusable and retrievable knowledge-based EM for BIM-based constructability assessment. To achieve this goal, this study focused on commercial building projects due to the lack of skilled workers for commercial construction projects in the United States (Albattah et al., 2015, Dai et al., 2009). In addition, because of the benefits of applying constructability at the early design stage discussed in this chapter, this study focused on the required constructability knowledge for the schematic design phase (pre-detailed design phase). The level of detail in the constructability assessment model was limited to the main building components, including structural frame, roof, slab, internal wall, external wall, and staircase. For each building component, this study focused on assessing the constructability of common construction systems within the U.S. construction industry. In addition, the tradeoff between cost and constructability of designs is not in the scope of this research. The EM developed in this study is compatible with IFC2x3 schema.

Organization of the Thesis

The aim of this research was to improve the design and construction processes by creating an EM for BIM-based constructability assessment of designs, and this thesis describes the process of creating the knowledge-based EM and its suitability for a BIM-based constructability assessment of commercial building designs.

This chapter presented the motivation, objectives, research questions, and scope of this research. Chapter 2 provides a brief description of constructability and discusses previous research studies focused on constructability assessment of buildings. In addition, it discusses the efforts of NBIMS in developing information standards and practices for improving information delivery and operation processes. Gaps in the current design and construction processes are summarized at the end of the chapter. Chapter 3 describes the research methodology of this study and shows how we can create an EM for BIM-based constructability assessment of designs. The validation method is also discussed at the end of the chapter. Chapter 4 discusses the analysis and results of surveys and interviews for developing the constructability assessment model. Chapter 5 elaborates on the process of creating the EM for the constructability assessment of designs. Chapter 6 demonstrates the results of validating the constructability EM via an experimental study. Chapter 7 discusses the conclusions of this thesis and summarizes the main findings.

CHAPTER 2

LITERATURE REVIEW

Currently, designers and construction managers usually operate separately during the design process. Designers are trained to concentrate on form and aesthetics in their designs, while construction managers focus on meeting schedule deadlines and reducing the costs of construction. Since many designers lack a thorough knowledge of the construction processes, they often ignore construction requirements and constraints in their building designs, resulting in the necessity for redesigns or design changes that may contribute to increased costs and time delays.

This conflicting approach to design by designers and construction managers motivated us to develop a quantitative model to allow designers to extract essential data for assessing the relative ease of their design's construction. Such a model can minimize the overall time and cost of the design process and reduce the need for later design changes. The intellectual merit of this research is to generate a reusable BIM-based constructability assessment exchange model that allows designers to extract essential data for reviewing the constructability of commercial building designs.

This chapter first outlines the definition of the constructability concept and its attributes and then presents the current state-of-the-art developments in constructability assessment.

Constructability at the Early Design Stage

In the past, someone such as a master builder reviewed the constructability of designs, and later, project participants exchanged information prior to construction to determine the best design solutions (Uhlik and Lores, 1998). In the 1970s, researchers found that the integration of construction and design increases the cost efficiency and quality of projects (Uhlik and Lores, 1998). In the 1980s, the Construction Industry

Institute (CII) researched this domain and defined constructability as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objectives" (CII, 1986). Because critical design decisions are made early in the process in selecting building structural systems, materials, equipment, and dimensions and areas, CII highlighted the importance of integrating constructability knowledge into design prior to the start of the detailed design or construction stages in order to reduce redesign, rescheduling, and cost of construction projects (Russell et al., 1992).

Tatum (1987) explored the impact of improving constructability in project planning, site layout preparation, and construction method selection at the conceptual design stage. Developing project plans at this early stage helps designers acquire a better advance understanding of construction sequences and schedules, as well as the project's procurement tasks (Tatum, 1987). Moreover, preparing site layouts at the conceptual design stage enables managers to achieve maximum usage of a construction site, including personnel and material access, and more efficient construction operations (Tatum, 1987). Selecting construction methods at this initial stage also results in an efficient construction cost estimation, including cost of construction equipment, labor, and materials (Tatum, 1987).

CII's Constructability Implementation Approach

CII grouped constructability studies into two categories, administrative solutions and implementation methods. The administrative solutions category refers to studies focusing on constructability implementation guidelines and increasing collaboration among the parties involved in a project. Studies in the implementation methods category address possible cost-saving construction methods such as prefabrication, preassembly, or any method in which multiple activities can proceed concurrently (Russell et al., 1992). In general, the aim of studies in both categories is to increase safety and quality and to reduce the cost and time expended on projects. To facilitate these goals, CII has introduced different approaches to implementing constructability within construction projects, as listed below (Russell et al., 1992).

- *Construction Management Historical Practice*: In this approach, captured data from in-house personnel and contract documents creates all the inputs for constructability management; however, this approach cannot estimate the value of constructability practices.
- *Constructability Contract Documents*: This approach uses data captured from contract documents to create constructability knowledge or plan review checklists during the detailed design phase. This approach also lacks a method for estimating the value of constructability efforts.
- *Constructability Services*: This approach involves a single point effort, associated with a preconstruction approach, including reviewing the costs of different design alternatives.
- *Constructability Design Review*: This approach utilizes personnel review designs based on plan review checklists to ensure that designs are accurate, cost efficient, and compatible with project constraints.
- *Quality Improvement Program*: In this approach, managers track constructability efforts and their impact on the quality of projects, but the benefits from such constructability efforts are difficult to ascertain.
- *Specialized Formal Constructability Programs*: Managers in this approach capture the constructability inputs of a project during the early design stage, then they generate constructability procedures for the project and track their impact. The generated constructability procedures and their impact are usually unique for every single project.

- *Standard Constructability Guidelines*: In this approach, organizations usually follow a constructability manual including constructability knowledge and experience obtained from various projects (e.g., CII in the United States and CIRIA in the United Kingdom). Since constructability efforts are widely accepted in this approach, organizations usually implement them without tracking their relevant impact.
- *Comprehensive Tracking*: The organizations using this approach to access databases that include various constructability philosophies captured from previous projects. These databases enable personnel to review prior constructability efforts and their benefits, such as cost and time saving, and then relate them to their own projects. However, in this approach, someone must record and keep track of the constructability efforts and their outcomes for use in future projects.

Design-related Constructability Assessment

In addition, Fischer, M. (1991a) introduced the following categories for design-relevant constructability knowledge:

- construction methods (application heuristics), referring to the general properties of projects such as total project area;
- horizontal and vertical constraints of structural elements (layout knowledge), containing items of knowledge relevant to the vertical and horizontal layout of structural elements, such as the distance between beams;
- dimensional constraints of structural elements (dimensioning knowledge), including the dimensions of structural members such as the length of a column or the section of a beam;

- constraints and requirements of structural details (detailing knowledge), referring to items of knowledge relevant to decisions about the requirements of construction methods such as structural erection sequences; and
- external factors (exogenous knowledge), covering potential exogenous constructability variables such as soil conditions.

Challenges of Applying Constructability at the Early Design Stage

Although constructability implementation at the early design stage is important, certain challenges can prevent the efficient implementation of constructability. For instance, one challenge is a failure to incorporate construction input in the early project phase (O'Connor and Miller, 1994). Such an incorporation assists in meeting all design requirements at the lowest construction cost and in reducing disputes between designers and construction personnel (Mendelsohn, 1997). Additionally, the lack of early incorporation negatively affects constructability in project plans, site layouts, and construction methods (Tatum, 1987). For example, the optimum use of a construction site, including sufficient space for personnel and materials, as well as the selection of appropriate construction methods and the acquisition of the required materials to meet a project's budget, all result from consideration of constructability early in a project (Tatum, 1987).

One of the other barriers to the early implementation of constructability is a reluctance to change on the part of design and construction professionals (Uhlik and Lores, 1998). For instance, designers usually prefer to create designs based on their preferred construction methods and then select contractors who are able to implement the chosen methods, but since they may lack construction knowledge and experience, their selected methods may not align or coordinate with a project's construction requirements and constraints. Another barrier of implementing constructability at the early stage of consecution projects is designers' lack of sufficient time, resources, and knowledge to review different design alternatives and pertinent costs. Similarly, construction managers do not have enough time to assess the total cost of different design alternatives based on the selected construction methods (Ballal, 1999). A constructability assessment model can help to overcome these challenges by allowing designers to assess designs and construction methods at the early design stage prior to construction.

Constructability Assessment Methods

Several studies have developed various computerized constructability improvement methods, which can be grouped into three categories (Navon et al., 2000). The first category refers to databases that include constructability problems and enable designers to look for solutions for potential problems; however, in this method, designers must first be aware of problems in order to find solutions, although they usually lack sufficient constructability knowledge to identify such problems. The second category includes systems recommending solutions for improving specific constructability problems within designs, but this method cannot analyze a given design to inform designers of potential constructability problems. The third category can analyze designs against constructability requirements, but this category is mostly based on 3D, not object-oriented, representations. Thus, designers cannot review constructability constraints relating to specific details such as materials, equipment, element types, and construction methods.

Constructability Knowledge Formalization

Construction knowledge can be represented either qualitatively or quantitatively. Through qualitative representation, researchers have proposed various guidelines or concepts extracted from the knowledge of construction experts. For instance, O'Connor et al. (1987) proposed various constructability concepts for the engineering and procurement phase of projects such as standardization for minimizing the number of component variations; preassembly engineering for facilitating fabrication, transportation, and installation; and review of specifications. In addition, Hanlon and Sanvido (1995) implemented a constructability repository that includes design rules, lessons learned, resource constraints, and external constraints. Raviv et al. (2012) conducted a survey to measure the effectiveness of implementing constructability concepts in construction projects. To assess the constructability of designs, Ugwu et al. (2004) employed rule-based agents to create a constructability knowledge framework and ontology-driven solutions to construction problems. Bakti et al. (2011) documented constructability factors affecting the constructability of sea water structures in Indonesia and created a checklist to assist designers during the review of their designs. Likewise, Kannan and Santhi (2013) explored and listed factors affecting the constructability of climbing formwork systems in India and compared types of formwork based on cost, time, sustainability, safety, and quality indices. Soemardi (Soemardi, 2000) proposed a virtual reality-based prototype that designers can use to review the erection process and estimate the constructability of their design based on visual observation.

Through quantitative representation, designers have proposed numerical models for evaluating the constructability of building design. For instance, Horn (Horn, 2015) defined a model for lateral deflection and strain energy metrics to assess both the constructability and structural performance of designs in the conceptual design stage. In the proposed approach, to measure the structural performance, the Horn study used the Karamba Analyze tool for the lateral deflection and strain energy metrics and a formula based on sizing for the structural weight metric. The Horn study proposed and explored some formulas and rules for evaluating the constructability metrics, including standardization member length, trucking requirements, node member connectivity, node angle connectivity, and cross section variation, but the Horn study was limited to only topology optimization for truss structures. Jarkas (2012) estimated labor productivity based on the impact of constructability attributes such as the diameters of rebar, the quantity of reinforcement installed, the thickness of walls, the geometry of floors, and the intensity of wall curvature. BCA (2014) developed an assessment model that adopted various building design scores for various structural systems. In addition, Lam et al. (2007) conducted expert interviews with experienced construction professionals to develop a constructability assessment model that encapsulates various building elements such as structural frames, slabs, envelopes, roofs, and internal walls. First, they conducted a survey with construction professionals in Hong Kong, which led to a finding that "coordinating drawings and specifications," "site/ground investigation for urban sites," "considering effects of below-ground work on surrounding buildings," "updating specifications and removing ambiguities," and "allowing safe sequence of trades for high rise buildings" are important contributions by designers to improving constructability. They then conducted expert interviews with experienced construction practitioners to quantify the constructability assessment of building designs in Hong Kong, which led to their quantification of the overall constructability scores for various building elements. However, because Lam et al.'s research was limited to construction in Hong Kong, the study's results may not be directly applicable in other countries.

Building Construction Systems

Most constructability studies focus on a small number of building design components, but a few studies have developed a comprehensive model for an entire building. Navon et al. (2000) explored rebar constructability problems such as a small distance between adjacent bars resulting in lower concrete cover around the bars, bent-up bars causing more difficulty in the manufacturing and installation processes, a slab supported by beams causing congestion between mesh in slabs, and stirrups in beams. They then developed a rebar constructability model that checks the density, the coverage, and the collision of rebar and recommends feasible solutions. Fischer (1991b) also developed a knowledge-based system for reinforced concrete structures that acquires knowledge from construction professionals and conveys it to engineers for the preliminary structural design. Jiang, L., et al. (2014) identified the essential construction information within a BIM model for assessing the constructability of formwork systems at the early design phase. In their study, they highlighted that automating the constructability review of designs at the early design phase results in more constructible solutions. Jiang, L. and Leicht, R. M. (2015) continued their research and developed an automated rule-based checking system for assessing the constructability of formworks in cast-in-place concrete projects. For instance, one rule checked by the system provides, "IF a floor-to-floor distance is less than 4.3 m (or 14 ft), THEN a conventional wood system is acceptable" (Jiang and Leicht, 2014). Their research was limited to formwork constructability and overlooked some important factors in the decision-making process such as availability of materials, labor needs, and equipment requirements. Ugwu et al. (2004) represented the application of ontologies in the assessment of the constructability of steel frame structures. Jarkas (2012) developed a model for assessing labor productivity for rebar installation in in-situ reinforced concrete walls. The model included various constructability factors such as rebar diameter, quantity of reinforcement, and wall thickness in reviewing constructability. Moreover, Soemardi (2000) used a virtual reality-based system that enables designers to visualize the construction process of precast concrete elements so that they can gain a more comprehensive understanding of both the design and erection processes, allowing them to assess the constructability of various building construction methods. BCA (2014) and Lam et al. (2007) demonstrated constructability assessment models for a precast concrete system, a structural steel system, a cast in-situ system, and a roof system within entire building projects.

Building Information Modeling

BIM is one of the most effective modeling technologies in the architecture, engineering, and construction (AEC) industries (Eastman et al., 2011b). With BIM technology, designers can easily and effectively share and coordinate data involving all views of a model (Eastman et al., 2011b). BIM represents a set of data about an object such as geometry, properties, and locations to produce, communicate, and analyze building models (Eastman et al., 2011b). Many people mistakenly think that any 3D model is a BIM model; however, a BIM model includes data and attributes about objects. For instance, SketchUp contains only 3D data of objects and no data regarding the objects' attributes, so it does not utilize BIM design technology. Rather, a BIM model includes different attributes such as geometry and location of elements, boundary conditions, loads, and material properties (Nielsen and Madsen, 2010).

BIM can support and improve many aspects of projects such as design, construction, and fabrications. BIM increases the overall quality and performance of designs by enabling designers to evaluate design alternatives prior to generating a detailed building model. In addition, BIM improves collaboration because designers can easily share their project requirements and understand the design requirements and constraints of other project teams (Eastman et al., 2011b). Designers are also able to predict cost, schedule, and materials of designs at the early stage of design processes so that they can make better decisions in choosing design alternatives (Eastman et al., 2011b). Moreover, designers are able to identify any design errors prior to construction and efficiently manage project data. Thus, BIM will be a requirement for the future of designs and construction (Autodesk, 2007).

Building Information Modeling and Interoperability

BIM transforms digital representations of models from two dimensional (2D) to 3D object-oriented drawings (Jeong et al., 2009). NBIMS defines BIM as: "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle" (NIBS, 2007). In the past decade, BIM has been a central paradigm and a shared-knowledge resource that enabled designers to manage a large amount of information for building 3D models (Chao et al., 2013). In addition, BIM enables designers to estimate construction time, cost, materials, and carbon emissions, and make more efficient decisions throughout a project's lifecycle (Chao et al., 2013).

One of the major challenges in the current BIM platforms arises in the exchange of 3D geometric shapes, defined using a set of relations and rules known as a parametric model, from one application to another, because most of the rule sets in the parametric models differ from one BIM platform to another (Eastman et al., 2011b). To solve these interoperability issues, previous studies developed a number of tools or standards. Currently, most design software supports three different interoperability methods, as follows (Burt, 2009):

- In-house interoperability formats, in which software vendors develop their own mapping structures, which can read the proprietary file format of BIM platforms;
- Application programming interface (API), in which software vendors write a well-developed interface that can translate files from different providers; and
- Industry Foundation Classes (IFC), for which the International Alliance for Interoperability (IAI) developed a neutral object-based file format for data exchange, which contains a set of data about objects (such as beams, columns, and slabs), processes, relations, property sets, and other information (buildingSMART, 2015a).

An IFC-based EM enables designers to access a rich product-modeling schema that includes a standardized structure of components and a model data of their geometry, topology, and materials (Venugopal et al., 2012); and IFC is the most popular of these three data exchange methods (Burt, 2009). However, because BIM platforms have different IFC exchange implementers, data exchange is often unreliable (Venugopal et al., 2012). To solve this issue, buildingSMART developed model view definitions (MVDs) to define exchange requirements using IFC (Venugopal, 2011). A number of the developed MVDs and exchange models are described below.

Construction Operations Building Information Exchange (COBie): This exchange method refers to specifications of information exchange for facility managers during the life-cycle of a project. The COBie specifications contain essential information that should be captured or exchanged for use by facility managers in maintaining, operating, and tracking systems and assets. The COBie standard supports the business process link between supply chain management and the quality assurance process and identifies essential information to be exchanged among disciplines (East, 2007).

Wall Information Exchange (WALLie): WALLie includes information exchange used to represent walls in BIM software. Project parties can use WALLie to represent information about walls that can be understood by everyone. The advantage of the WALLie standard is that it provides a valuable database that minimizes the loss of information (buildingSMART, 2015d). This exchange model currently is under development.

Building Automation Modeling information exchange (BAMie): This exchange method exports data into a MVD from BIM software platforms. For example, facility managers can use BAMie to easily export the required MVD for delivery tasks. BAMie focuses on required information of the entire system life-cycle, required information of project disciplines, and required information of model objects (buildingSMART, 2015d).

HVAC information exchange (HVACie): HVACie contains the required information exchange for the elements, connections, assemblies, and systems of a facility (buildingSMART, 2015d).

Steel Structure Project (AISC): The AISC standard supports data exchange for structural steel projects and includes methods of data transference and sharing for the entire lifecycle of projects (DBL, 2013).

Precast Concrete Project (PCI): This exchange method supports information exchange for precast concrete projects in different phases of a precast concrete project. The PCI contains information exchange for various phases of precast concrete projects such as contracting, architectural design review, and manufacturing (buildingSMART, 2015d). The workflow process of a PCI project consists of capturing detailed information, modularizing information, creating object instances, and implementing EMs (Venugopal et al., 2012).

Other Research in Exchange Model Domains: Recently, many researchers have been focused on exchange model domains as a method for improving the BIM implementations in design processes. As an example, Lee et al. (2014), developed and documented required EMs for multi-zone airflow analysis so that engineers can estimate and predict the airflow performance of buildings in conceptual architectural designs.

Summary

A summary of the studies presented in this literature review appears in Table 1. Only a few studies outside of the United States have developed quantitative models for assessing the constructability of building designs. Because other countries have unique building codes, standards, and construction methods, U.S. designers cannot employ these models, and studies of the U.S. construction industry primarily focus on proposing qualitative guidelines for improving the constructability of building components. Further, even though the constructability of commercial buildings differs from that of residential buildings, previous studies and research have not differentiated between the constructability of designs for each building type, even though their construction involves different method and materials. For instance, the structures of commercial buildings in the United States are typically made of steel, concrete, or precast components, while the structures of residential buildings are generally made of wood. Moreover, commercial construction projects often require more skilled workers and larger and more advanced equipment. Despite these differences, no constructability assessment model specifically developed for commercial buildings is currently available. In addition, in spite of BIM's many advantages, none of the earlier research generated an efficient and accurate set of standard exchange models to access a reliable information exchange for a BIM-based constructability assessment of building designs. Thus, designers that adhere to U.S. building codes and construction requirements need a BIM-based quantitative constructability assessment model that will enable them to conduct an efficient exploration of the constructability of commercial building designs.

Table 1: A summary of literature review

Reference	Components	Scope of application	Qualitative guideline	Quantitative assessment model	Constructability attributes	Building construction systems	Country	BIM-based EM
(Surya Bakti et al., 2011)	Sea water structures	–	✓	–	–	–	Indonesia	–
(Kannan and Santhi, 2013)	Formwork	Residential and commercial	✓	–	–	4 types of formworks	India	–
(BCA, 2014)	Building	All building types	✓	✓	Not specified	4 types of structural frame, 7 types of internal and external wall systems	Singapore	–
(Windapo and Ogunsanmi, 2014)	Building	–	✓	–	48	Precast and cast in situ structures	Nigeria	–
(Soemardi, 2000)	Building	Residential	✓	–	–	Precast concrete structures	Indonesia	–
(Lam et al., 2007)	Building	All building types	–	✓	63	5 types of structural frames, 5 types of slabs, 4 types of roof, 5 types of external wall, 3 types of internal wall, no staircase	Hong Kong	–
(Tauriainen et al., 2012)	–	–	–	–	–	Review constructability	–	Recommended
(Raviv et al., 2012)	Building	Residential and commercial	✓	–	12	–	–	Recommended

Table 1: A summary of literature review (continued)

Reference	Components	Scope of application	Qualitative guideline	Quantitative assessment model	Constructability attributes	Building construction systems	Country	BIM-based EM
(Horn, 2015)	Façade	_	✓	✓	10	Truss steel frame	U.S.	–
(Jiang et al., 2015)	Formwork	_	✓	–	_	Cast-in-place concrete frame	U.S.	–
(Ruby, 2008)	Building	_	✓	–	_	Steel frame	U.S.	–
(Fischer, 1991b)	Building	_	✓	–	_	Cast-in-place concrete frame	U.S.	–
(CII, 1986)	Building	_	✓	_	_	_	U.S.	–
This Study	Building	Commercial	_	✓	79	11 types of structural frame, 7 types of slab, 10 types of roof, 11 types of external wall, 9 types of internal wall, 4 types of staircase	U.S.	✓

CHAPTER 3

RESEARCH METHODOLOGY

This section presents three important foundations for formalizing and mapping the constructability assessment of structural design EMs into IFC schema entities, relations, attributes, and functions. The first section represents an overview of the research framework, and the subsequent section explains each phase of the research in detail. Finally, the last section presents the method of validation and verification of the proposed EM.

Introduction

The current research focuses on improving design processes by proposing a knowledge-based EM for BIM-based constructability assessment of commercial building designs so that designers can access structured data models to help in assessing the constructability of their designs and have the ability to reuse the models in other projects.

The developed methodology intends to address the research questions and achieve its goals through the following methods:

1. model requirements,
2. model design,
3. model implementations, and
4. model validation.

Figure 2 illustrates a generalized view of the research. The “model requirements” step explores the required factors affecting the constructability of designs. The “model design” step identifies the process of creating EMs for constructability assessment of commercial building designs. The following step, “model implementation,” maps EMs and requirements into the IFC schema. Finally, “model validation” verifies the accuracy and correctness of implementing the EM for the constructability assessment of commercial building designs.

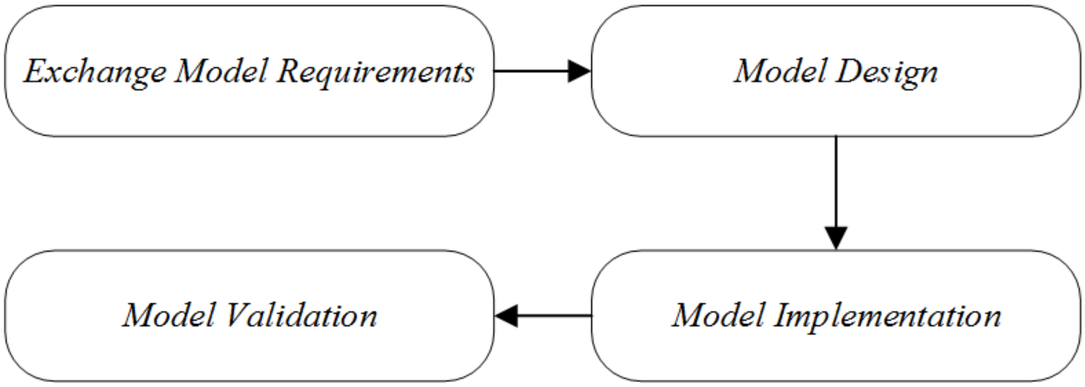


Figure 2: A summary of the research methodology

Overview of the Framework

The methodology of this study consisted of six main phases: constructability attribute identification, constructability attribute classification, construction system identification, constructability model development, constructability EM, and validation (Figure 3.) The first two phases entailed identifying and ranking essential constructability attributes based on their importance and the third phase involved identifying common construction systems in the United States. Before conducting the surveys, we had the Georgia Tech Institutional Review Board (IRB) review the study protocol to ensure compliance with human research subject regulations. In the fourth phase, we used the results of the previous phases to formulate a constructability assessment model. Then, we created an EM for BIM-based constructability assessment of commercial building designs. Finally, the last phase included validating the EM we developed. The following sections describe the details of each phase.

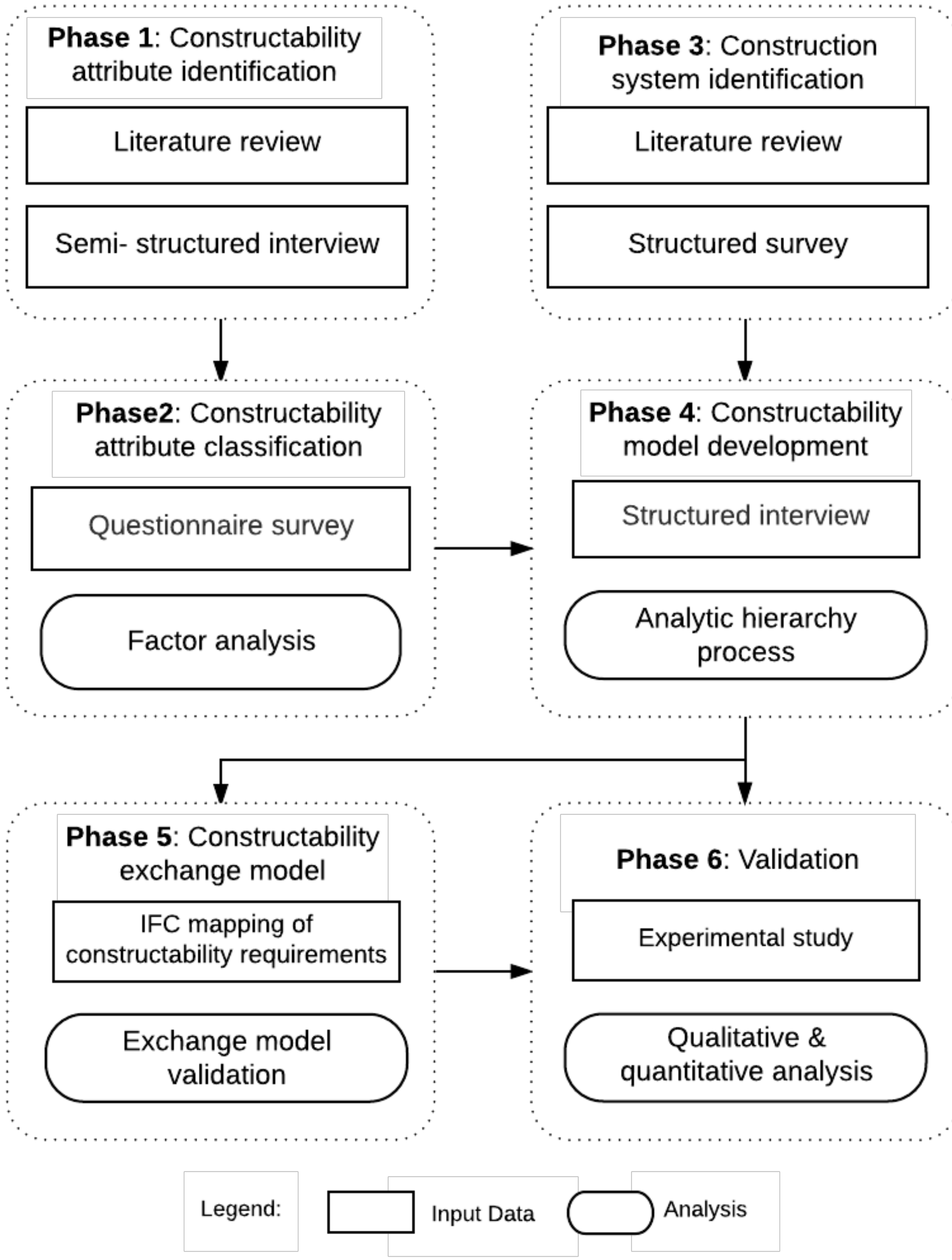


Figure 3: Details of the research methodology

Phase 1: Identification of Constructability Attributes

This phase involved two stages. In the first, we conducted a comprehensive literature review to identify various attributes of construction projects. We reviewed a number of academic journal and conference papers and selected 18 publications that explicitly identified constructability attributes, from which we extracted common attributes. In the second stage, we conducted a semi-structured interview with 29 randomly chosen construction professionals, including structural engineers, architects, construction managers, and contractors. The goal of the interview was to validate the attributes that we had extracted from the 18 publications.

Phase 2: Classification of Constructability Attributes

Questionnaire Survey

Using the results of the first phase, we created an online survey to determine the importance of the identified constructability attributes. The survey consisted of three main sections: demographics, importance of attributes, and comments. The demographics section contained questions about the participants' level of education; the location, type, and size of their companies; their job positions; and the length of their prior construction experience. The second section asked participants to rank the constructability attributes of building design based on a five-point Likert scale (not important/slightly important/moderately important/very important/extremely important.) Finally, the last section asked participants to provide additional comments. To ensure that the attributes we identified were comprehensive, we asked participants to suggest other attributes that they considered important but which were not contained in our list.

We predicted that the participants, who represented a broad spectrum of professionals, would fall into three types: those who had extensive knowledge about the level of importance of the constructability attributes, those who were knowledgeable about only some of the attributes, and those who answered questions carelessly or without reading them first. We added a “don’t know” option for the second group of respondents. In addition, we added a number of quality-check instructions such as “Please ignore this question,” “Please leave this question blank,” and “Please skip this question” to capture low-quality responses for the third group of respondents.

Before distributing the questionnaire, we conducted a pilot study with eight participants to assess its quality and clarity. Using the participants’ feedback, we modified and improved the questionnaire. To ensure comprehensiveness of the samples, we used multi-stage sampling. This technique entailed first randomly selecting ten construction companies from each of the 50 U.S. states and then randomly selecting four to five individuals from each company. Before emailing the survey to the participants, we checked their LinkedIn pages or websites to ensure their eligibility to participate. One of the criteria for eligibility was the amount of construction management experience in commercial projects the participants had as general contractors or subcontractors. Once we eliminated those without sufficient experience, we distributed the questionnaire to between 40 and 45 construction professionals from each state, for a total of 2,100 individuals.

We sent the participants a set of documents including an introduction, and a consent form prior to conducting the survey. The introduction included a short description of the researchers, the aim of the project, and the structure of the questionnaire. The consent form notified the participants about the survey procedures, benefits, and compensation. It also informed them that the researchers would keep their personal information confidential and that they had the right to leave the study at any time without giving any notice or incurring any penalty.

Factor Analysis

To reduce the large set of variables in the research into a small set of variables without excluding important data, we conducted a factor analysis, a technique for defining underlying structures and relationships among variables (Hassan and Bakar, 2008). Two important applications of factor analysis are confirmatory factor analysis (CFA) and exploratory factor analysis (EFA). CFA applies to the validation of hypotheses and their underlying latent construct(s), and EFA refers to the identification of relationships among variables and the discovery of an underlying structure of factors for a set of variables. However, both approaches explain whether the factors are correlated or uncorrelated (Hassan and Bakar, 2008, Suhr, 2006).

Phase 3: Identification of the Construction System

To determine the current construction systems in the United States, we reviewed various publications such as books, manuals, and technical papers and prepared a list of common construction systems. To validate the list, we conducted 14 structured interviews with construction professionals and asked them to review and add any construction system they believed was missing.

Phase 4: Development of the Constructability Model

Analytic Hierarchy Process

A systematic approach for decision-making using a pairwise comparison of a set of attributes and alternatives is referred to as an analytic hierarchy process (AHP) (Bhushan and Rai, 2007). Decision makers and managers benefit from this method in multi-criteria decision-making situations that require selection, prioritization, resource allocation, and prediction (Bhushan and Rai, 2007). This method contributes to solving and analyzing problems in a more structured and organized manner. It also enables decision makers to compare multi-attribute qualitative and quantitative data (Gilleard and

Wong Yat-lung, 2004). Using this approach, we deconstructed a problem into its subcomponents, including goals, criteria, sub-criteria, and alternatives, and then we prioritized the importance of the alternatives to the goals through the pairwise comparison of criteria and alternatives with respect to the goal using a qualitative scale (An et al., 2007, Saaty, 2008). In this study, the goal at the top of the hierarchy was improving the constructability of commercial building designs (see Figure 4.) The criteria are the various constructability factors, and the attributes are the building systems.

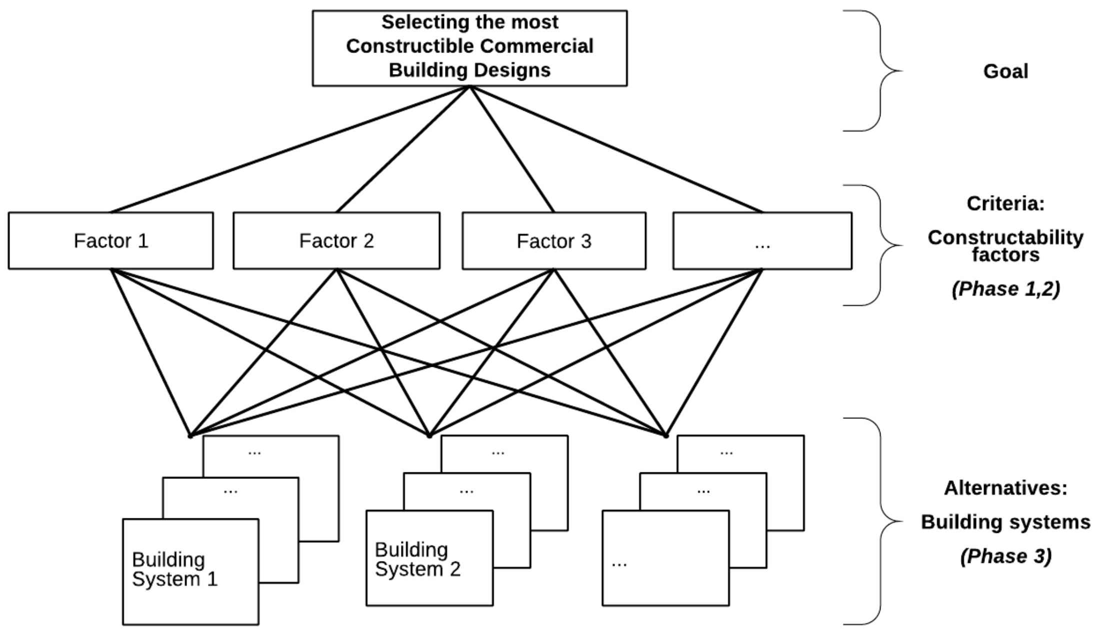


Figure 4: AHP decision hierarchy

A number of studies, among others, have employed the AHP for implementing multi-criteria decision support systems in the AEC industries, including the

- *cost estimation model*, in which An, S.H. et al. (2007) conducted the survey with 22 cost managers to create a cost estimation model;
- *contractors selection model*, in which Fong, P.S. and Choi, S.K. (2000) implemented the survey with 13 participants to build a technique for selecting contractors who can manage price, time, resource, and quality of projects and are

qualified based on their past performance and experience and Mahdi, I.M. et al. (2002) also used the AHP-based survey to apply multi-criteria decision support systems for choosing contractors;

- *procurement selection model*, in which Cheung, S. et al. (2001) did the survey with 15 experts for a complex project;
- *architectural consultants' selection model*, in which Cheung, F.K.T. et al. (2002) conducted the survey with 53 respondents in Hong Kong to generate a model for the selection of architectural consultants;
- *advanced construction technology selection model*, in which Skibniewski, M.J. and Chao, L. (1992) used AHP to quantitatively evaluate the benefits of advanced construction technologies on quality and schedule performances, operating costs, and safety;
- *maintenance management model*, in which Shen, Q. et al. (1998) used AHP to prioritize maintenance works;
- *facility management model*, in which Gilleard, J. and Yat-lung, P. (2004) applied the AHP-based survey to assess the benefits of selecting a facility management strategy on project performance, productivity, financial performance, compliance, compliant and accident frequency, and customer satisfaction; and
- *project delivery selection model*, in which Al Khalil, M.I. (2002) implemented AHP to prioritize project delivery methods by including project characterization, owner needs, and owner preferences.

Structured Interviews

To capture the knowledge of construction experts for creating a constructability assessment model, we developed an AHP- based survey. As noted above, the questionnaire contained four sections: demographic questions, questions aimed at determining the relative importance of constructability factors (one matrix, fifteen pairwise comparisons), questions relating to the relative importance of building systems with respect to a specific constructability factor (thirty-six matrices, 1,206 pairwise comparisons), and a comments section. In the second section, participants compared the relative importance of the constructability factors with respect to the goal using the quantitative scale presented by Saaty (1987) (i.e., from 1 = equal importance to 9 = absolute importance), as further outlined in Table 2. For instance, one question asked how important is "building element standardization" to the "efficient use of resources" in order to "improve the constructability of commercial building designs"? One possible answer could be "strongly important," expressed as the number "5." In this manner, qualitative measures were converted into quantitative numbers in the AHP. In the third section of the questionnaire, participants compared various construction building system alternatives with respect to each criterion. For example, regarding the "building element standardization" factor, one question asked how constructible is "cast in-situ RC frame" compared to the "cast in-situ loadbearing wall"? During the interview sessions, we also asked participants to rate the relative importance of the building components (out of 100) with respect to the constructability of commercial building projects.

Table 2: AHP pairwise comparison scales (Saaty, 1987)

Intensity of Importance	**Definition**	**Definition**
1	Equal importance	Two elements **equally** important to achieve the goal
3	Moderate importance	One element **moderately** favored over another to achieve the goal
5	Strong importance	One element **strongly** favored over another to achieve the goal
7	Very strong importance	One element **very strongly** favored over another to achieve the goal
9	Absolute importance	One element **absolutely** favored over another to achieve the goal
2,4,6,8	**Intermediate values** between two adjacent judgments	

Before emailing the AHP survey to participants, we conducted a pilot study and modified the survey based on the feedback we received. Because of the importance of commercial construction knowledge and experience to the development of the assessment model, we decided to ask the construction experts to respond to survey questions regarding their backgrounds (e.g., whether they had ever worked as construction contractors, construction managers, or project managers on any commercial construction project; the types of commercial buildings on which they had worked ; and the years of experience they had in commercial building construction). Based on their responses, we invited those who had acquired extensive experience in commercial construction projects to participate in the survey. In the interview sessions, we elaborated on the objective of the study and explained its architecture. Using various examples, we demonstrated how the participants should perform the pairwise comparisons in the second and third sections of the survey. After the interview, we sent out surveys to those who attended the meeting.

Data Analysis

To analyze the data, we adopted a method proposed by Saaty (2000). First, we used the weighted geometric mean to incorporate the opinions of all decision makers equally (see Equation A below) (Saaty, 2000, Grošelj et al., 2011). Then we normalized the value in the column of the pairwise comparison matrix by dividing each table value by the total value of the column. Next, we computed the importance ratings (i.e., the weight of each factor) to obtain the prioritization of factors contributing to the enhancement of constructability in building designs by calculating the average of all values pertinent to each factor (i.e., the eigenvector, or vector of priorities). These importance ratings represent the correlation between the constructability and construction building systems. Afterwards, we estimated the consistency index (CI) of the responses, which is the product of the maximum eigenvalue and the total value of each column (see

Equations B and C). The acceptable consistency ratio (see Equation D) was expected to be less than 10% (Saaty, 2000). The pertinent equations are expressed as follows:

$$w_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}$$ Equation A- (Saaty, 2000),

$$Aw = \lambda_{max} w$$ Equation B- (Saaty, 2000),

$$CI = (\lambda_{max} - n)/(n - 1)$$ Equation C- (Saaty, 2000),

and

$$CR = CI/RI$$ Equation D- (Saaty, 2000),

where *w* represents the principal eigenvector, λ_{max} the maximal corresponding eigenvalue of the pair-wise comparison matrix, *CI* the consistency index, *RI* the random index (from Table 3), and *n* the number of factors.

Table 3: Random index (RI)- (Saaty, 2000)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

After establishing the priority factors, we determined how each alternative affected each criterion. Through the same process by which we prioritized the factors, we weighted the alternatives (i.e., construction building systems) with respect to the goal. After calculating all of the priorities and CIs, we calculated the relative weights of each construction building system (alternatives). To calculate the final priority, we added the multiplications of each factor weight by its alternative weight.

Phase 5: Defining Constructability Exchange Model

This phase aimed to create an EM, which is the key aspect in representing and sharing data as it provides the bridge between different BIM platforms. NBIMS defined standard and efficient terminologies for information exchange within building models and which supports project disciplines including AEC and operations (Eastman et al., 2009a).

Information Delivery Manual (IDM)

Information delivery manuals (IDMs) focus on the exchange requirements of end users to ensure that the information flow is effective (Eastman et al., 2009a). In developing IDMs, the first step is to determine the required types of geometry, properties, or relations of elements for defining the purpose of the information exchange relating to constructability. IDMs provide an integrated information source for the design processes and exchanges by determining different tasks and sub-tasks of all organizations involved during the life-cycle of projects (IUG/IDMC, 2010). For example, IDMs contain information regarding how the information is relevant, who uses and benefits from the information, and how software solutions support it (IUG/IDMC, 2010).

The reasons for implementing IDM definitions as a part of the methodology in this research include the following (IUG/IDMC, 2010, Eastman et al., 2009a):

1. IDMs enable project participants to easily exchange information about a specific topic in a required level of detail;
2. IDMs capture information for all disciplines and all stages of a project;
3. IDMs provide users with a good understanding of work processes;
4. IDMs assist project participants to collaborate in a single phase without any duplicative or repetitive tasks; and
5. IDMs provide essential information for developing EMs.

Figure 5 shows the IDM hierarchical structure including process models, EM descriptions, and exchange requirement levels for developing IDMs (ACI, 2012). In this research, the IDM hierarchy identifies the general processes of constructability. The first level is the process model, which identifies tasks, non-model exchanges, and the BIM model exchange. It also provides essential details and definitions of information exchange for future implementations. The next level is the EM description that identifies the relevant tasks of constructability and the implementation phases, as well as the fundamental information for their implementation. Then, the exchange requirement level provides details and information about the functional requirements for the content of the data exchange, such as entities and their attributes and relations. This study employs these functional requirements for developing model view definitions.

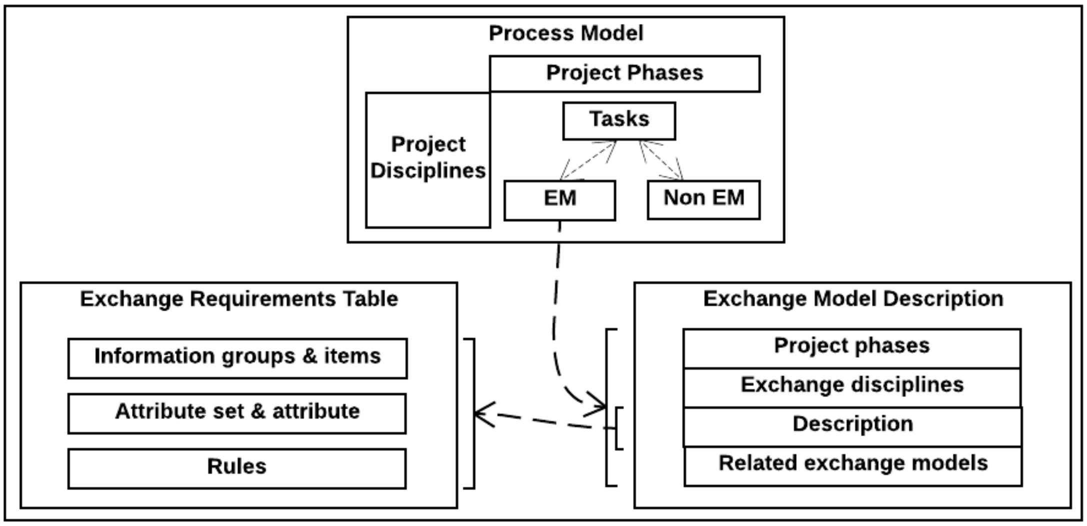


Figure 5: IDM hierarchical structure, adopted from (ACI, 2012)

Throughout the previous phases of the methodology, this study determined information exchange requirements for assessing the constructability of designs, which resulted in the identification of functional data exchange requirements and workflow scenarios for specifying the semantic characteristics of the product data models, as well as the definition of an exchange among all entities involved in the process maps of constructability assessment. Next, this step documented the captured information needed to support specifications of information exchange for constructability assessment into an IDM.

Exchange Models (EMs)

The next step after defining IDMs for the constructability assessment of designs was developing IFC concepts by using IFC entities and property sets. The functional specifications of outputs of an IDM is an MVD (Eastman et al., 2009b). MVDs define a logical and a comprehensive subset of the complete IFC models and specify IFC implementation levels to support workflows defined in the IDMs (Eastman et al., 2009b). MVDs consist of multiple EMs that contain multiple concepts. The proposed constructability assessment EM enables designers to easily design, model, edit, and update structural and architectural models after running the constructability model. Figure 6 illustrates the development process of MVDs adopted from NBIMS, (2007). The current study focuses on the steps in the gray box to create an EM that can be used on any other MVDs to assess the constructability of designs.

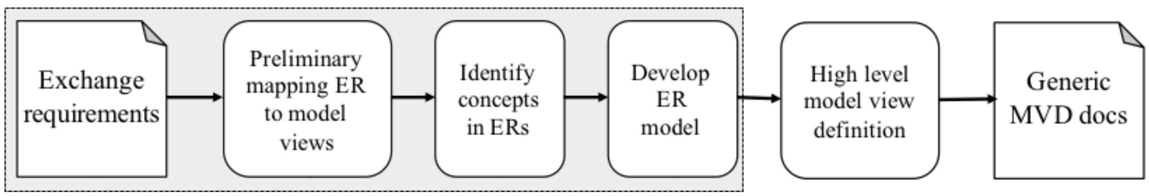


Figure 6: The development process of MVDs, (NBIMS, 2007)

Exchange Model Validation

The goal of this phase is validating the EM translator with IFC (see Figure 7.) To validate the BCAEM in this study, we created a comprehensive building model to test a large number of concepts and also simple models to test only one concept, or a few concepts. Based on the defined terminology and rules, the test models consisted of various object instances such as beams, walls, and slab elements. The aim of developing test models was to test every concept of the EM thoroughly and also to validate combinations of concepts within the EM. Since the process of IFC validation and certification is normally a time-consuming and expensive task, this research validated all of the test models against sets of conditions using the IfcDoc application developed by buildingSMART International (buildingSMART) (buildingSMART, 2015b). The IfcDoc application automatically generates an IFC documentation for the baseline IFC documentation and MVDs (Chipman, 2012). It is an open source tool enabling software vendors to review the accuracy of their translators and to do their own debugging. For validation purposes, the IfcDoc automatically generates a validation report in both IfcDoc and HTML formats. Any error that occurs during the validation can result from a bug in either the test model or the rule logic. Figure 8 shows an example of a validation report in the IfcDoc application.

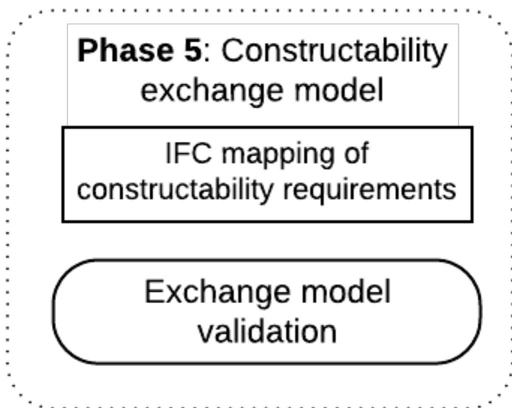


Figure 7: Phase 5 of the research methodology

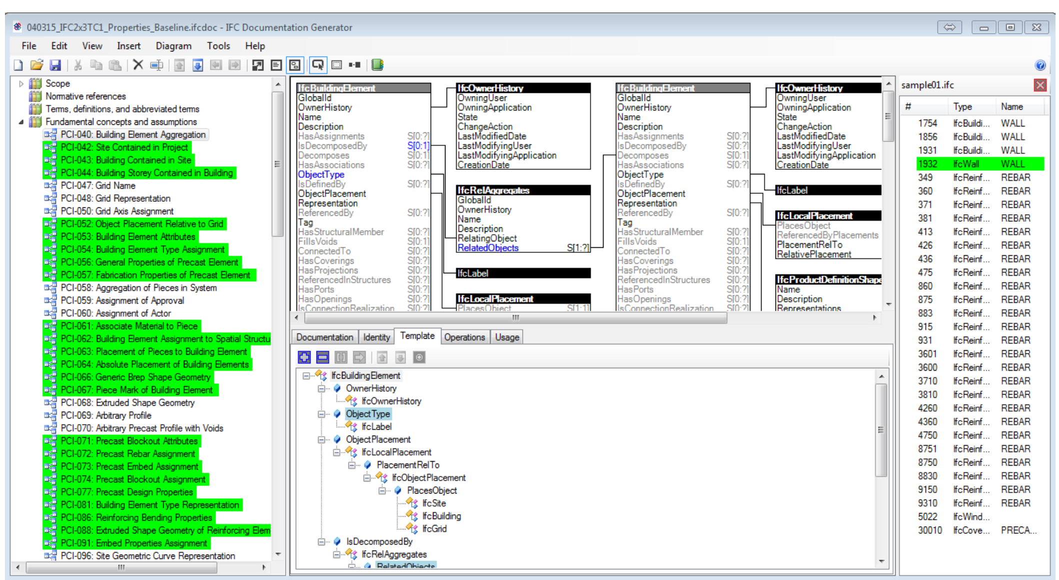


Figure 8: An example of the validation report generated by IfcDoc application

Phase 6: Validation

The goal of the validation was to examine the overall application of the BCAEM in construction projects (see Figure 9.) The hypotheses of the validation were, as follows:

> "Integrating construction knowledge into the design stage via BCAEM would help designers with: 1) Exploring the constructability of designs in less time, 2) Assessing the constructability of designs more accurately, and 3) Formalizing the method of constructability assessment."

The validation of the BCAEM was based on the experimental study to test the goal of the validation. The experiments consisted of: Task 1 -- rating the constructability of each BIM design on a scale of 0 to 100, Task 2 -- improving the constructability of the given BIM design by providing a list of ideas and feedback on how to increase the constructability of the design (e.g., change brick walls with precast walls), Task 3 -- using the BCAEM to calculate the constructability of the designs, and Task 4 -- filling out the post-experiment questionnaire. Chapter 6 explains the experiment's design, process, and results in more details.

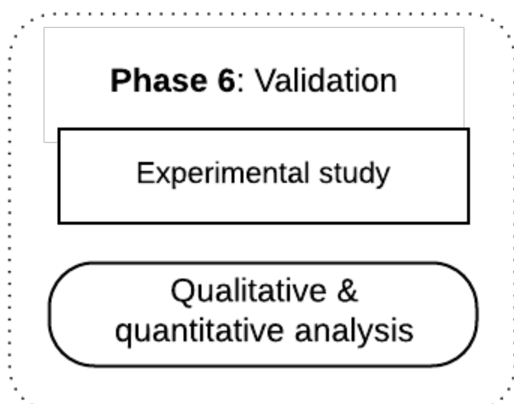


Figure 9: Phase 6 of the research methodology

CHAPTER 4

RESULTS FROM INTERVIEWS AND SURVEYS

With more designers beginning to adopt constructability requirements and constraints, this study first investigated the current construction workflow and then explored the constructability attributes that integrate constructability requirements into the early design phase. This chapter presents the results of this study's exploration of current constructability implementation and constructability attributes and factors as well as its development of a constructability assessment model.

Identification of the Constructability Attributes (Phase 1)

As a result of the comprehensive literature review discussed in Chapter 2, we identified 79 essential constructability attributes (Windapo and Ogunsanmi, 2014, Sulankivi et al., 2014, Tauriainen et al., 2014, Kuo and Wium, 2014, Tauriainen et al., 2012, Jarkas, 2012, Ruby, 2008, Lam et al., 2007, Wong, 2007, Navon et al., 2000, Fischer and Tatum, 1997, Fischer, 1991b, O'Connor et al., 1987), as illustrated in Appendix A. These attributes can be classified into two categories, design and construction (Figure 10). In the design category, the constructability attributes relate to simplification, standardization, coordination, prefabrication, and design flexibility. In the construction category, the attributes relate to planning for and foreseeing construction activities such as managing sites, spaces, resources, safety, and utility.

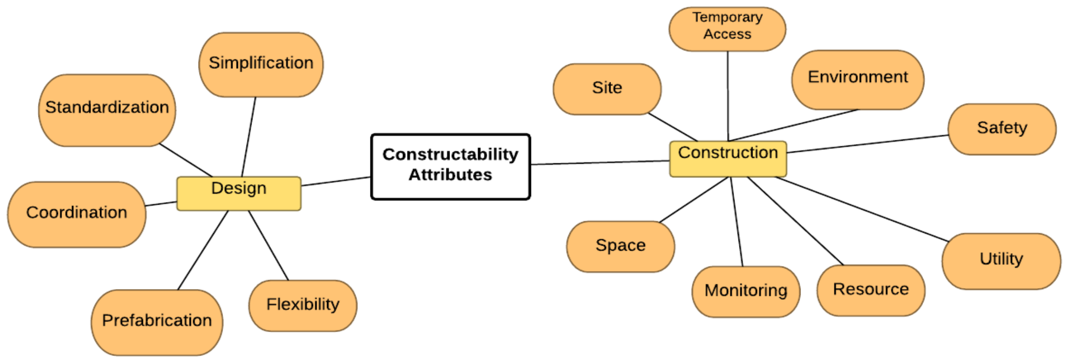


Figure 10: Constructability attributes

Current Design Process and its Challenges

This study relied on semi-structured interviews to obtain a better understanding of construction problems arising from the current lack of constructability implementation and to confirm the constructability attributes captured through the literature review. We conducted these interviews between October 2015 and December 2015. Twenty-nine construction professionals including designers, construction managers, contractors, and project managers were randomly chosen to participate in the survey. Twelve individuals out of twenty-nine had more than ten years of construction experience, ten individuals had between five and ten years of experience, and the rest had less than five years of experience. Seventeen of the interviewees had a bachelor's degree, ten interviewees had a master's degree, two interviewees had a Ph.D. degree, and the rest of them had a certification in design and construction domain.

During the interviews, we asked our subjects to describe their common design and construction processes and the relevant issues involved. Based on our discussions, we found that for each company the implementation of the design process depended on the project contract and conditions. Project contracts usually contain information and details about different aspects of the project, the construction disciplines involved, and the deliverables to be generated. Therefore, to coordinate all the design goals from the various disciplines, clients and service providers first read the contracts to understand the project's scope. Then, project design teams involving contractors, architects, structural engineers, and mechanical engineers arrange a kick-off meeting in which they review drafts provided by each party and modify them as needed. They also provide a model organization program and BIM process maps addressing the project's phases, the parties involved, and their responsibilities and tasks. Then all the teams start to work simultaneously using a server-based system. Depending on the company and the project, the design teams may access their own exchange portals or commercial server systems such as ProjectWise or Trimble Connect for sharing and viewing project information. For instance, if design teams are collaborating in the Trimble Connect server, each design team uploads their models in the server nightly or weekly to ensure that other teams have access to the latest version of the designs and all designs are aligned. If any project discipline rejects requested or applied changes, then design teams will set a coordination meeting and discuss the proposed changes in an effort to find solutions that work for all disciplines. For example, in one project, the structural engineers rejected changes made by the project's architects in the location of columns and braces, but the architects insisted on their proposed changes. To solve this conflict, the structural engineers decided to use a buckling-restrained braced system that would satisfy both architectural and structural requirements.

The survey demonstrated that the interactions among the project disciplines differed depending on the project delivery method used. However, we discovered that designers mostly preferred the design-bid-build (DBB) delivery method. More than one-half of the participants mentioned that in other project delivery methods, contractors usually prefer to add their own inputs regarding construction methods and seek to control all details within the designs, affording designers less flexibility and design freedom. Therefore, designers usually prefer to create designs that define the construction methods and then select contractors who are able to implement the predefined methods, while contractors prefer to implement the construction methods in which they have more expertise.

Because architects focus on their own aesthetic building elements, which differ from structural requirements, sometimes architectural and structural designs may not be aligned and coordinated due to time limitations. Once the architects submit their designs to the contractors, they designate which parts of the architectural designs and the structural designs the contractors should follow. For example, if the locations of openings in the architectural and structural designs do not match, then structural engineers may clarify that beams must be located a certain distance from the edge of any opening to highlight the misalignment for the contractors. However, this process in not efficient because the contractors then have to spend extra time to create a coordinated construction design. Moreover, structural engineers, leery of potential liability, may hesitate to provide a work instruction that dictates how the contractors should build a design, creating an even bigger challenge for a contractor trying to figure out a solution for any design conflicts. This methodology decreases the efficiency of both the design and construction processes.

As discussed earlier, in the current design workflow, architects generally start with some simple visual concepts, and then all the disciplines meet and walk through the details of a project and the contract. They also discuss any possible issues that they may face in a project and set up a schedule and milestones for completing certain tasks in each phase of the project. The main reason for developing milestones is to determine the essential information needed to be exchanged among the disciplines. The kind of information and the level of detail to be exchanged differs depending on the project and the contract. For example, if engineers include seismic ratios in their designs, they have to apply early analysis and construct analysis models so that architects can know the potential locations of braces, columns, the main seismic building elements, or the details of stairs that typically have complex geometries. In this situation, structural engineers often provide advice about seismic designs for architects, so that they can coordinate their architectural models with the structural design requirements.

The participants discussed some design process failures affecting the construction phase. The first failure highlighted by participants was lack of proper communication. For example, in a one-story steel building project that included four surgery rooms, the designers were not aware of the location and conditions of the construction site during the design phase. As a result, they designed beams deeper than needed Once construction began, the contractor discovered the problem and planned to ask designers to reanalyze the design, but because the project schedule was tight, he had to build based on the existing design, with no time for redesign, resulting in $200,000 in extra costs. However, this problem could have been avoided, if the contractor had been involved from the beginning of the project or if the designers were aware of the construction requirements. The second failure was the failure to consider resource availability during design. For instance, when three large projects were simultaneously under construction in Atlanta, other construction projects in the city experienced a shortage of local labor and materials. The third failure noted was a lack of design coordination. Designers usually do not have enough time to complete their designs and coordinate them with other disciplines, so they submit their designs and expect that the contractor will figure out any misalignment within the designs. Additionally, when contractors also have to start construction earlier, they may not have enough time to review the designs. An example mentioned by one participant involved a lack of design coordination between structural and mechanical designs. The designers did not have enough time to coordinate their designs with other disciplines prior to submitting them to the contractor, who did not review the designs. When the contractor began mechanical installation, he found that the structural beams clashed with the mechanical HVAC systems. He had to ask the designers to reanalyze the designs to fix this issue. The designers redesigned the beams to add holes to accommodate the HVAC systems, requiring extra time and resulting in extra cost.

However, this issue could have been prevented if the designers had coordinated their designs in the design phase, which may have resulted in earlier detection of the problem. Complex geometry was another issue discussed by the participants. To increase the structural performance and stability of a building, designers may employ complex geometry that is difficult to build, especially when any complex connections are comprised of multiple elements. The next highlighted issue was difficulty in choosing the best design alternatives and construction methods. Since designers lack sufficient knowledge of construction requirements and constraints, they usually cannot select a design alternative that is easier and quicker to build.

In summary, based on the interviews, we determined that designers need a construction knowledge-based system enabling them to assess constructability of building designs so that they can choose the optimum design and construction systems in terms of quality, time, and cost of construction as well as productivity of construction labor.

Classification of the Constructability Attributes (Phase 2)

Questionnaire Survey

In this phase, we conducted a pilot study with a small group of respondents (eight individuals) to investigate the correctness of the identified constructability attributes of building design and to optimize the format of the questionnaire. The final version of the questionnaire included the following three sections:

1. Demographic questions regarding state, level of education, type of organization, job position, years of experience in construction and current position, and size of company;
2. Questions seeking a rating of the relative importance of the identified constructability attributes based on a five-point Likert Scale with options

of “not important,” “slightly important,” “moderately important,” “very important”, and “extremely important” as well as a sixth option of “don’t know;”

3. Questions designed to identify constructability attributes of building design missing from the questionnaire survey and to elicit any suggestions or comments.

The questionnaire survey was hosted on https://www.google.com/form through my google account. Appendix B is a paper format of the questionnaire survey. We distributed the questionnaire based on a multi-stage sampling in which we first randomly selected ten construction companies from each state in the U. S. and then randomly targeted four to five individual general contractors, designers, project managers, sub-contractors, and suppliers from each company. Before emailing the survey to the chosen participants, we checked their LinkedIn pages and/or websites to ensure that they were eligible to participate in the survey. We distributed the questionnaire among 40-45 individuals from each state for a total of 2100 construction professionals. We kept the survey open from February to April 2016.

Demographic and Participant Characteristics

Out of 2,100 emails sent, we received 350 responses, representing a response rate of 17 percent, an acceptable rate for a web survey (Shih and Fan, 2009). We checked the quality of responses and excluded responses in which participants filled out any “Please leave this question blank” question, leaving 298 valid responses out of 350. Figure 11 illustrates the distribution of participants within the U.S. and their individual states. As shown in Table 4, about 11% of the respondents had high school degrees, more than 57% bachelor’s degrees, 28% master’s degrees, and 4% doctorates. About 72% of the respondents were contractors, 13% were consultants, and 15% were from organizations such as construction management and engineering firms. The majority of respondents

(41%) worked at small companies (less than 100 employees), about 32% at small-to-medium-sized companies (100-999 employees), 22% at medium-sized companies (1,000-9,999 employees), and 5% at large companies (more than 10,000 employees). More than 71% of respondents had more than fifteen years of experience in commercial construction projects, about 14% had between nine and fifteen years, and the remaining had less than nine years.

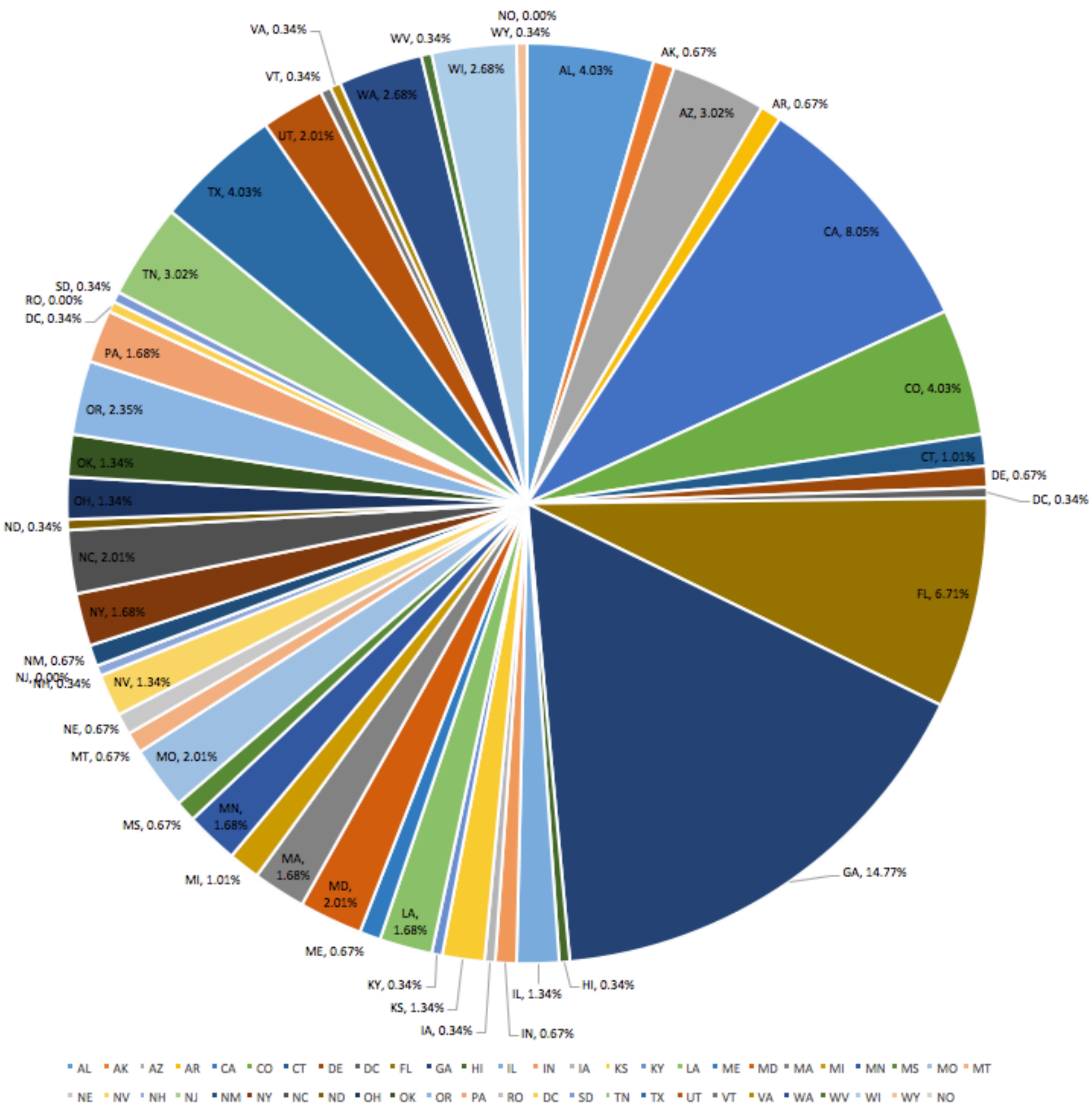


Figure 11: Distribution of participants within the U.S.

Table 4: Demographics of participants

Variables		Percentage (no.)
Level of Education	H. S. Diploma	7.74% (23)
	Bachelor's	57.24% (170)
	Master's	27.95% (83)
	Ph.D.	3.03 (10)
	Other	4.04% (12)
Type of Organization	Contractor	71.62% (212)
	Consultant	13.18% (39)
	Owner	2.70% (8)
	Other	12.50% (27)
Size of company	Small (less than 100 employees)	41.28% (123)
	Small-medium (100-999 employees)	32.55% (97)
	Medium (1000-9999 employees)	21.81% (65)
	Large (10000 employees or more)	4.36% (13)
Current Position	Architect	3.7% (11)
	General Contractor	26.94% (80)
	Project Manager	20.54% (61)
	Structural Engineer	6.06% (18)
	Sub-contractor	0.67% (2)
	Supplier	1.35% (5)
	Other	40.74% (121)
Years of experience in construction	Less than 3 years	3.38% (10)
	Between 3 and 9 Years	10.47% (31)
	Between 9 and 15 years	14.53% (43)
	More than 15 years	71.62% (212)

Factor Analysis

The minimum sample size for the factor analysis is 200 participants (Floyd and Widaman, 1995, Jöreskog and Sörbom, 1989, Gorsuch, 1983), so our sample was sufficient. We estimated the internal consistency of the five-point Likert scale using Cronbach's Alpha. The results showed the reliability of the data with a Cronbach's Alpha coefficient of 0.974. In addition, to assess the suitability of the data for factor analysis, we conducted the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. The KMO index was 0.946, exceeding the requirement of at least 0.5, and the Bartlett's test of sphericity was significant ($p<0.05$), making it suitable for factor analysis (Hassan and Bakar, 2008).

To determine the number of factors and the maximum number of components in each factor, we used EFA, which extracts factors with the maximum possible variance in the correlation matrix of measured variables (Floyd and Widaman, 1995). The results of the EFA showed seventeen factors with eigenvalues equal to or greater than one with a maximum of seven and a minimum of one component in each of the seventeen factors. Since the number of variables in each component should be at least three (Comrey and Lee, 2013), we used a scree plot to determine the number of components to retain. In a scree plot, each component contains less variance than preceding components, and components in the steep curve before the first point at which the flat line trend begins have the most variability (Floyd and Widaman, 1995). Therefore, we retained components above this point and rejected the rest without discarding significant variance (Williams et al., 2012). As a result, we obtained six constructability factors from seventy-nine constructability attributes (as shown in Figure 12).

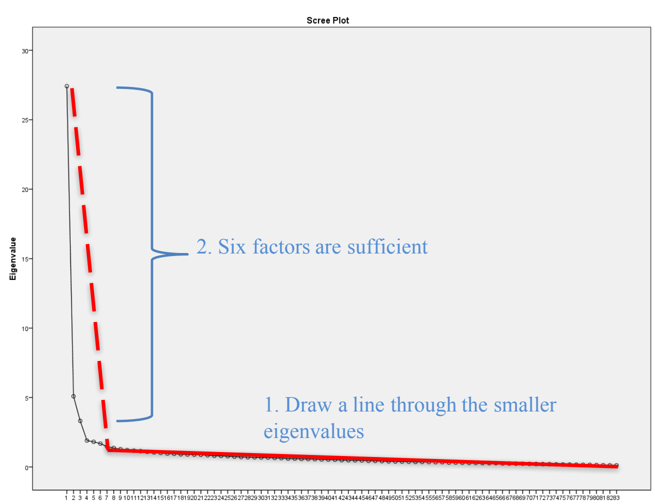


Figure 12: Scree test criterion

To simplify and clearly interpret the results of the factor analysis, we rotated the factors using orthogonal (i.e., uncorrelated) or oblique rotation (i.e., correlated) (Suhr, 2006). To select between orthogonal or oblique rotations, we ran a direct oblimin to determine whether or not any correlation between components was less than - 0.32 or greater than 0.32 (Brown, 2009). Since we found values outside this range, we selected oblique rotation. Then, for each factor, we examined all of the variables and proposed a name that satisfied the majority of the constructability attributes. In addition, we conducted an interview session with nine construction professionals, each with more than ten years of experience in construction, to confirm the naming of each constructability factor. The purpose of the interview was to ensure that these labels reflected the theoretical and conceptual intent of their relevant constructability attributes as shown in the tables below. The final formalized constructability factors are as follows: 1) building details and design components (Table 5); 2) resource intelligence and alignment (Table 6); 3) design standardization (Table 7); 4) construction site logistics planning and scheduling (Table 8); 5) innovation (Table 9); and 6) design review and coordination (Table 10).

Table 5: Constructability Factor 1 -- Building details and design components

Constructability Attributes
Rebar diameter
Type of reinforcement
Wall thickness
Distance between adjacent bars
Number of beams used to support floor areas
Quantity of reinforcement
Traditional timber formwork
Round columns
Metal formwork
Average slab panel area in floors
Area and number of holes in building elements
Strut-free basement construction
Element angle connectivity
Number of floors
Curved beams
Use of spray painting
Allowing fewer wet trades on site
Number of individual slab panels formed within the floor due to beam-framing plan
Traditional external scaffold (e.g., independent or putlog)
Field-welded connections
Bolted structural connections
Size (i.e., length, width, and height) of components
Transportation road capacity
No formwork (i.e., a stay-in-place precast concrete form system)
Self-climbing perimeter scaffold

Table 6: Constructability Factor 2 -- Resource intelligence

Constructability Attributes
Resource analysis and scheduling (e.g., time, cost, and quality)
Allowing economical use of labor and machinery (e.g., balancing between labor and machinery use to reduce overall cost)
Implementing measures to improve productivity and performance
Allowing use of know-how and labor skills available locally
Optimizing materials usage
Allowing use of a wide range of materials to fulfill required performance
Labor/skills usage optimization
Allowing use of machinery and equipment available locally
Construction cost
Flexible design
Designing to aid visualization of finished work
Designing for optimum use of machinery and equipment
Designing for locally available materials/fittings/products/sub-assemblies (including imports)
Specifying robust and suitable materials/components or giving directions for protecting fragile items (e.g., precast stairs)
Specifying tolerances for as many items as possible
Suggesting non-obligatory construction methods for contractors to consider
Causing less environmental nuisance (e.g., noise, vibration, waste water, chemical waste and dust) to surroundings
Optimizing use of materials and substances

Table 7: Constructability Factor 3 -- Design standardizations

Constructability Attributes
Simple installation
Minimizing scaffolding needs
Maximizing preassembly work
Uncomplicated geometry, layout, and shape for floors and buildings
Enabling simplification of construction details
Minimizing onsite works
Standardization maximization
Maximizing vendor shop fabrication
Minimizing temporary structural supports
Allowing modular layout of components
Number of connections
Allowing easy connection/interfacing between components
Wall curvature intensity
Standardized member length
Variability of element sizes in floors (i.e., repetition criteria)
Optimizing the mix of offsite work and onsite work
Minimizing underground work

Table 8: Constructability Factor 4 -- Construction site logistics planning and scheduling

Constructability Attributes
Efficient site layout and storage
Site conditions (e.g., soil)
Allowing sufficient working space for labor, materials and machinery on site
Use of cranes/lifting equipment
Access lanes to construction site
Considering fall protection in designs
Weather consideration (e.g., adjusting timing to avoid carrying out structural work, external finishes, etc., during rainy/typhoon season)
Scheduling and ordering element assemblies
Allowing safe sequence of trades (e.g., heavy M&E machinery hoisted into position before building is fully enclosed)
Crane-lifted perimeter scaffold/fly cage

Table 9: Constructability Factor 5 -- Innovation

Constructability Attributes
Innovative/efficient construction methods
Use of ceiling inserts/cast-in brackets to support M&E fittings
Visualization tools implementation
Allowing for early removal of temporary support to leave clear working space

Table 10: Constructability Factor 6 -- Design review & coordination

Constructability Attributes
Examine possible clashes in the design (e.g., building services clashing with reinforcements)
Coordinating drawings and specifications
Clear and complete design information
Coordinating tolerance specifications for interfacing items (e.g., window frame connected to window opening)
Ensuring sizes and weights of materials and components safe for workers to handle using commonly available machinery
Stability of the structural frame during erection

Identification of the Construction System

From the literature review (BCA, 2014, Wong, 2007, Kuo and Wium, 2014) and the interviews with the 12 construction professionals, we identified the common construction systems of structural frames, slabs, roofs, external walls, internal walls, and staircases (Table 11). For instance, some of the common construction systems of structural frames are the cast in-situ RC frame, the in-situ load bearing wall, masonry, and the metal stud frame.

Table 11: Common construction building systems

Construction Building Systems			
Structural Frame	Cast in-situ RC frame	**Internal Wall**	Cast in-situ wall with applied finishes
	In-situ loadbearing wall		Concrete block/brick with applied finishes
	Masonry		Dry wall (partitions)
	Metal stud frame		Light weight brick
	Post-tensioning structure		Light weight panel
	Pre-engineered metal building		Metal stud
	Pre-tensioning structure		Precast wall with applied finishes
	Precast concrete frame		Precision block wall
	Steel encased in concrete (composite structure)		Traditional brick and plaster wall
	Structural steel with fire proofing	**External Wall**	Precast concrete wall with pre-installed windows and finishes
	Timber structural frame		Curtain wall
Slab	Flat slab		In-situ concrete wall
	In-situ RC slab		Precast sandwich panel with in-situ filling
	Post tensioned concrete		Block wall with applied finishes
	Pre-stressed concrete		Brick wall with applied finishes
	Precast slab with in-situ topping		Metal cladding
	Steel deck with in-situ concrete topping		Prefabricated timber panel
	Timber frame flooring system		Full height glass panel
Roof	In-situ concrete roof		Prefabricated timber
	Precast concrete roof		Dry wall system
	Pre-engineered metal building	**Staircase**	Cast-in-place
	Prefabricated timber roof truss		Prefabricated
	Steel decking		Steel
	Steel decking with in-situ concrete topping		Timber
	Steel truss roof with composite decking		
	Timber roof trusses		

Development of a Constructability Model (Phase 3)

Analytic Hierarchy Process

We independently interviewed 15 construction professionals who had worked as construction contractors, construction managers, or project managers on commercial construction projects such as municipal, office, retail, and religious buildings, hotels, sports stadiums, and restaurants within 26 states. Appendix C is a paper format of the AHP survey. About 70 percent of the interviewees in the AHP survey had more than 15 years of experience in commercial building projects. The consistency ratio of each comparison matrix in their responses was at a satisfactory level of less than 10% (Saaty, 1980).

The normalized results of the pairwise comparison and prioritization of the constructability factors are presented in Table 12. In this study, "Design Review and Coordination" has the highest priority for improving the constructability of commercial building designs and "Innovation" has the lowest. Similarly, the results of our comparisons of the building system alternatives with respect to the constructability factors and their priorities are presented in Table 13. Based on the findings, "Pre-engineered metal building" is the most constructible structural frame and "Post-tensioning structure" the least constructible. In addition, "Precast slab with in-situ topping" is the most constructible slab system and "Timber frame flooring system" the least constructible. The most constructible internal wall system is "Drywall" and the least is "Traditional brick and plaster wall." Based on the results, participants identified "Curtain wall" as the most constructible external wall systems and "prefabricated timber" as the least. Moreover, they highlighted "Pre-Engineered Metal Building" as the most constructible and "In-situ concrete roof" as the least constructible roof systems. Finally, the results show that "Prefabricated" and "Timber" are the most and the least constructible staircase systems, respectively. The relative importance of structural frames, slabs, internal walls, external walls roofs, and staircases in the constructability of a commercial building project is illustrated in Table 14. The results show that "Structural frame" and "Staircase" have the highest and the lowest rate of incorporation in the constructability of commercial building projects, respectively. Next, we formulated the following model for calculating the constructability of commercial building designs (Equation E). The minimum and maximum constructability scores calculated by this formula is 0 and 100, respectively.

> ***Constructability score of designs*** = *constructability score of structural system + constructability score of slab system + constructability score of internal wall system + constructability score of external wall system + constructability score of roof system + constructability score of staircase system*

OR

$$\boldsymbol{Constructability\ score\ of\ designs} = \{32[\sum(V_s * C_s)] + 12[\sum(A_l * C_l)] + 22[\sum(A_x * C_x)] + 9[\sum(A_n * C_n)] + 18[\sum(A_r * C_r)] + 7[\sum(A_t * C_t)]$$

Equation E,

where V_s = Percentage of total volume using a particular structural frame system

A_l = Percentage of total area using a particular slab system

A_x = Percentage of total area using a particular external wall system

A_n = Percentage of total area using a particular internal wall system

A_r = Percentage of total area using a particular roof system

A_t = Percentage of total area using a particular staircase system

C_s = Constructability index for a particular structural frame system (Table 13)

C_l = Constructability index for a particular structural slab system (Table 13)

C_x = Constructability index for a particular external wall system (Table 13)

C_n = Constructability index for a particular internal wall system (Table 13)

C_r = Constructability index for a particular roof system (Table 13)

C_t = Constructability index for a particular staircase system (Table 13)

W_s = Constructability importance of structural frame system (Table 14)

W_l = Constructability importance of slab system (Table 14)

W_x = Constructability importance of external wall system (Table 14)

W_n = Constructability importance of internal wall system (Table 14)

W_r = Constructability importance of roof system (Table 14)

W_t = Constructability importance of staircase system (Table 14).

Table 12: The relative importance of constructability factors

Constructability Factor	Constructability Indices
Design Review and Coordination	1
Building Details and Design Components	0.959
Construction Site Logistics and Scheduling	0.945
Design Standardization	0.777
Resource Intelligence and Alignment	0.656
Innovation	0.6

Table 13: The constructability indices of various construction building systems

Building Components	Construction Building Systems	Constructability Indices
Structural Frame	Pre-engineered metal frame	1
	Metal stud frame	0.681
	Precast concrete frame	0.676
	Structural steel with fire proofing	0.523
	Masonry	0.387
	Cast in-situ RC frame	0.386
	Pre-tensioning structure	0.386
	In-situ loadbearing wall	0.33
	Steel encased in concrete (composite structure)	0.309
	Timber structural frame	0.304
	Post-tensioning structure	0.298
Slab	Precast slab with in-situ topping	1
	Steel deck with in-situ concrete topping	0.968
	In-situ RC slab	0.834
	Flat slab	0.771
	Pre-stressed concrete	0.664
	Post tensioned concrete	0.564

Table 13: The constructability indices of various construction systems (continued)

Building Components	Construction Building Systems	Constructability Indices
	Timber frame flooring system	0.556
Internal Wall	Dry wall (partitions)	1
	Metal stud	0.893
	Precast wall with applied finishes	0.646
	Light weight panel	0.498
	Precision block wall	0.452
	Light weight brick	0.4
	Concrete block/ brick with applied finishes	0.365
	Cast in-situ wall with applied finishes	0.354
	Traditional brick and plaster wall	0.33
External Wall	Curtain wall	1
	Precast concrete wall with pre-installed windows and finishes	0.934
	Dry wall system	0.889
	Metal cladding	0.668
	Precast sandwich panel with in-situ filling	0.644
	Full height glass panel	0.635
	Block wall with applied finishes	0.507
	In-situ concrete wall	0.497
	Prefabricated timber panel	0.474
	Brick wall with applied finishes	0.469
	Prefabricated timber	0.445
Roof	Pre-engineered metal roof	1
	Steel decking	0.643
	Steel truss roof with composite decking	0.606
	Prefabricated timber roof truss	0.559
	Steel decking with in-situ concrete topping	0.461
	Precast concrete roof	0.45
	Timber roof trusses	0.342
	In-situ concrete roof	0.28
Staircase	Prefabricated	1
	Steel	0.736
	Cast-in-place	0.38
	Timber	0.357

Table 14: Importance of building components to constructability

Building Components	Weight
Structural Frame	32
Slab	12
Internal Wall	9
External Wall	22
Roof	18
Staircase	7
Total	*100*

Model Validation

The constructability assessment model can be validated qualitatively by interviewing construction experts or quantitatively by comparing the results of the current model with other such models. Since no other quantitative constructability assessment model exists in the United States, we chose to validate the model qualitatively. Thus, we asked five of the study's participating construction professionals to review and verify the model. The individuals selected are well-known construction experts, each with more than 20 years of experience in commercial building projects. Because these experts had participated in the previous steps of the research, they already knew the study's goals and objectives. We provided them the results of the AHP survey (Table 13), the assessment model (Equation E), and one example of how to use the model. We then asked them to validate the scoring of the building systems and the constructability assessment model and to describe how they would like the model to be improved in future studies. To give the experts ample time to examine the constructability model, we decided to send our survey via email. However, we asked them to send us clarifying questions or to request a face-to-face meeting if needed. We gave them one week to review the results and send us their feedback. After receiving their feedback, we presented them with a number of follow up questions to clarify their responses.

After receiving all of the feedback, we analyzed the responses for commonalities. We found that all of the respondents were in agreement with the model's scoring of the building systems. In one of our follow up questions we asked why the post-tension structure received the lowest ranking compared with the other structures. The construction professionals explained that post-tension structures are highly engineered and have a very challenging construction process, so they require skilled and experienced contractors and construction managers and can involve potential downside risks. For example, if cables are located too close to the surface, they can be susceptible to corrosion. In addition, if a cable is nicked or cut by after it is subjected to tension, the resulting damage could cause the entire slab to fail.

In addition to the scoring of the building systems, the construction experts agreed that the results of the constructability assessment model developed in this study were in line with their experience with the ease of construction of various commercial buildings. Some examples of the feedback received are as follows:

- the "[r]esults are aligned with my responses and views of these systems as it relates to constructability… I think the data you collected bore this out well;"
- the "[r]esults are accurately representative of my opinion;" or
- "[i]n terms of 'ease of getting it done', I mostly agree with the results."

To improve the model, participants highlighted the importance of integrating the constructability assessment model with a cost model so that project participants could examine how a selected method of construction would affect the overall cost of the project. For instance, if several acceptable construction options were available that would equally meet the performance requirements, an integrated cost model could help with selecting a less expensive option.

CHAPTER 5

BUILDING INFORMATION EXCHANGE MODEL

This chapter discusses the process of creating and validating the constructability EM based on a NBIMS approach. In previous chapters, we created an assessment model calculating the constructability score of building designs. To use this model, designers need to export the total area and volume of a particular construction system (e.g., masonry walls and steel structure). To ensure the accuracy and correctness of the information extraction, we should have consistent terminologies for components' names and properties, construction types, and elements quantities (volume and area) in building models. Thus, an EM is needed to standardize the required information and support transparent and robust information exchange for calculating the constructability of building designs. The following sections present the development of a constructability assessment EM.

Introduction

Construction project stakeholders need schemas to define the structure of information required for the processes of design, procurement, construction, operation, and maintenance (Bjaaland et al., 2012). To this end, NBIMS established schemas based on the International Framework for Dictionaries (IFD) Library for producing a single terminology database, including building entities such as building systems, components, or materials (Bjaaland et al., 2012). NBIMS also laid out generic guidelines for developing specialized model views, defined in terms of Industry Foundation Classes (IFC), which is a neutral object-based file format for data exchange and includes a set of data about components, processes, relations, property sets, and other details (buildingSMART, 2015a).

Since the IFC data model contains unique sets of definitions and rules and is an open international standards approach to BIM, project stakeholders use it to exchange data in a readable and understandable format from one BIM platform to another. However, IFC schema contains a broad range of details and a dataset pertinent to the full lifecycle of a project, so the project's participants often become overwhelmed with the amount of data available (Nawari, 2011). Thus, NBIMS proposed EMs as an approach for encoding information exchange during the lifecycle of building projects (NBIMS, 2007). EMs provide a set of required information and functionalities for data exchanges.

Exchange Model Development Process

According to NBIMS, the process of creating EMs has four steps (Figure 13) (NBIMS, 2007). Phase 1 involves capturing and identifying the needed exchanges and their relevant data sets for business processes within the building construction industry. Phase 2 describes the architecture of organizing the data captured in the previous phase into a particular exchange requirement model. Phase 3 includes the preparation and expression of relations between information concepts and specific elements available in the IFC schema so that software vendors are able to implement the standards. Finally, Phase 4 provides the EM's validation and its content. The following sections explain each of these phases in detail.

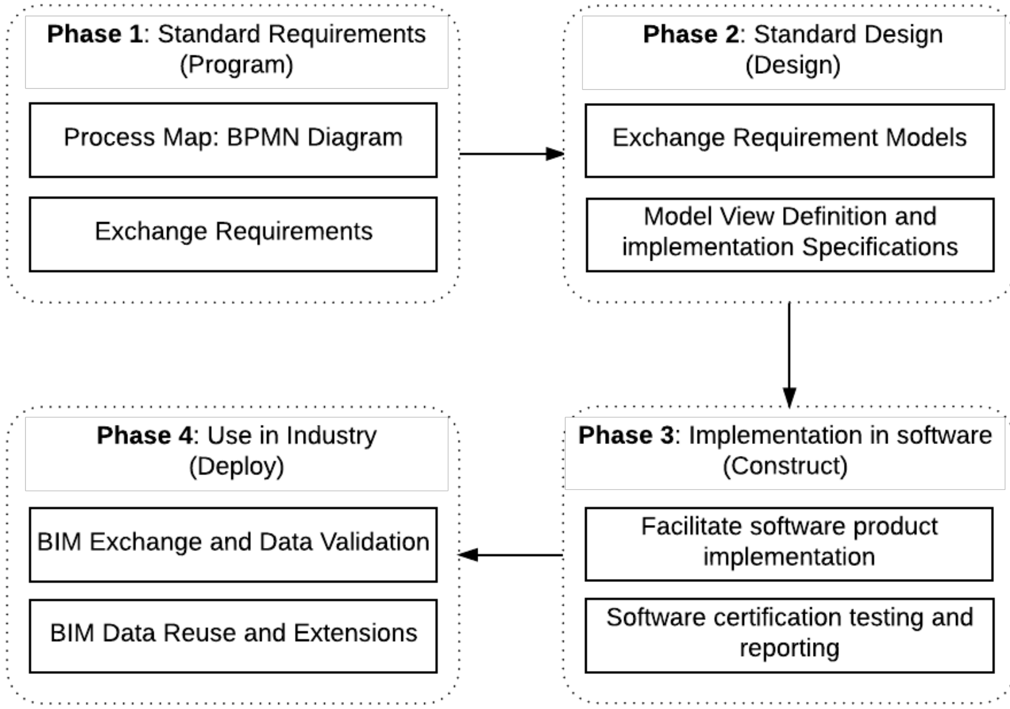


Figure 13: NBIMS development and use diagrams- (NBIMS, 2007)

Step 1: Creating the Process Map of Information Exchange

The first step in developing an EM is understanding the information required during the design or construction processes (Venugopal et al., 2012). To demonstrate when exchanges occur during the design process and to identify the senders and recipients involved in those exchanges, we used Business Process Modeling Notation (BPMN) (Eastman et al., 2009a). Figure 14 shows an example of BPMN for data exchange in the Precast/Prestressed Concrete Institute (PCI) MVD. The rounded white rectangles, called activity nodes, identify tasks; dotted-line arrows, called control nodes, show the direction of information flows (import or export); green boxes identify BIM-based EMs; and yellow boxes represent documents that are exchanged among project disciplines (Eastman et al., 2009a). Table 15, Table 16, Table 17 show templates of documentation defining the intentions of tasks, model exchanges, and non-model exchanges. To maintain consistency in terminology, Construction Specification Institute

(CSI) standardized the language used in construction and documented the standardized terminology in Omniclass codes (Omniclass, 2006). Based on the Omniclass standardization, all project phases, disciplines, and project organizations involved in a building project have a standard title and code. For instance, the design phase's code in Omniclass is 31-40 00 00 and structural engineering's code is 33-21 31 14.

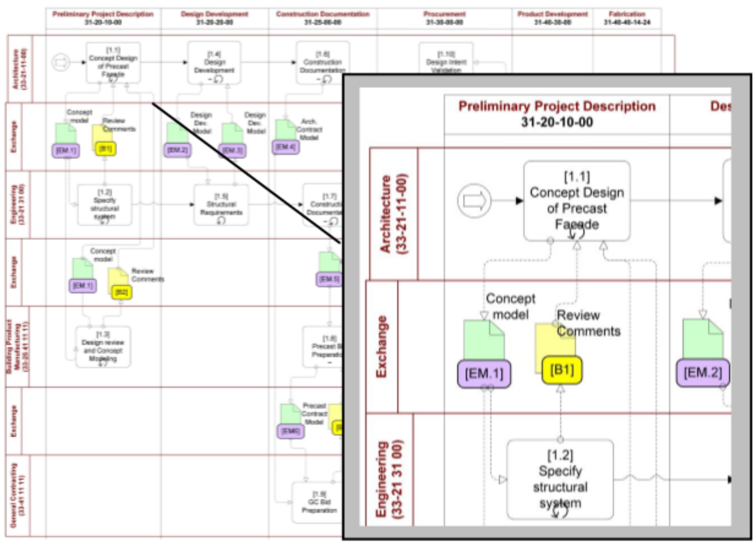


Figure 14: BMPN for information exchange in PCI NBIMS- (Zolfagharian and Eastman, 2015)

Table 15: Task description template- (Eastman et al., 2009b)

Type	Task
Name	Name and Omniclass project stage of the activity performer
Omniclass Code	Name and Omniclass project stage number in which the task occurs.
Documentation	Verbal description of: 1. The purpose of the activity 2. The task execution process

Table 16: Exchange model description template -- (Eastman et al., 2009b)

Project Stage	Omniclass design stage
Exchange Disciplines	Parties to this exchange From: To: By Omniclass discipline number and name. (can be > 2 disciplines, but using the same basic data).
Description	Verbal description of: 1. The purpose of the exchange 2. The required contents of the exchange 3. The optional contents of the exchange 4. Whether the exchanges are round trip or one-way
Related Exchange Models	1. Other exchanges with which this one interacts (proceeding and succeeding exchanges).

Table 17: Non-model exchange description template -- (Eastman et al., 2009b)

Project Phase	Omniclass project stage
Discipline from	Omniclass discipline number and name of the discipline generating this non-model information.
Discipline(s) to	Omniclass number and name of disciplines receiving the generated non-model information.
Information transmitted	Verbal description of: 1. The purpose of the exchange 2. The required contents of the exchange 3. The optional contents of the exchange
Typical formats	Formats in which the non-model information is exchanged.

Step 2: Defining the Constructability Exchange Requirements and Rules

After gaining an understanding of the data exchange, we needed to capture the detailed properties of various exchanges in each phase of construction projects and categorize them into a table as an IDM. It provides information and specifications in an understandable and reusable format. In the IDM's table, the properties should be classified according to whether they are considered "Required" (R) or "Optional" (O). "Required" means that if any of these objects or entities exist in a given building model, then the EM is valid only if these properties and their values are available in the exchange (Eastman et al., 2011a). In contrast, “Optional” means the constructability EM is valid whether or not these properties and their values are available in the exchange (Eastman et al., 2011a). Figure 15 shows an example of the IDM format for three EMs. For instance, as shown in Figure 15, the “assembly relations” attribute is a required specification in A_EM.1, P_EM.1, and S_EM.1, but the “structural loads” attribute is optional in all three exchanges.

				A_EM.1	P_EM.1	S_EM.1
Identity	Name, Function	Required?		O	O	O
Design constraints	Classification	Required?		O	O	O
	Use Occupancy	Required?		O	O	O
	Live Loads	Required?		O	O	O
	Wind Loads	Required?		O	O	O
	Fire Rating	Required?		O	O	O
	Importance Factors	Required?		O	O	O
	Seismic design requirements	Required?		O	O	O
Structural Loads	Classification	Required?		O	O	O
	Use Occupancy	Required?		R	R	R
	Fire Rating	Required?		O	O	O
	Importance Factors	Required?		O	O	O
Assembly relations	Located on site...	Required?		R	R	R
	Contains building systems...	Required?		R	R	R
Association relations	Other buildings on site...	Required?		R	R	R

Figure 15: Sample EM specification table

Step 3: Modularizing the Exchange Requirements into IFC

The third step in creating an EM is to translate the generated IDMs into a set of modularized pieces of IFC called concepts (Venugopal et al., 2012). Concepts specify details of exchange requirements as an IFC schema and are reusable in different EMs (Venugopal et al., 2012, Nawari, 2012). Each EM is comprised of one concept, or several concepts, that identify a modularized IFC exchange format for software vendors (Nawari, 2011). Moreover, the combination of multiple EMs creates a MVD, which is outside the scope of this research. Nevertheless, this study created a list of concepts, which can be reused in other MVDs such as PCI MVD, AISC MVD, and ACI MVD. To consistently develop IFC interfaces in BIM platforms, NBIMS published a template for documenting concepts and the rules of their implementation (Figure 16). The description section of the template contains IFC primary bindings and a list of implementation agreements associated with the various concepts (Nawari, 2011). Table 18 presents the purpose of each section in an IFC concept description file.

IFC Release Specific Concept Description <Title Field>-					
Reference	<Reference field>	**Version**	<Version field>	**Status**	<Status field>
Relationships	<Entity Field>				
History	<Version history field>				
Authors	<Author field>				
Document Owner	<Company field>				
<the description>					
<Example field>					
This document uses the official IFC Model View Definition Format of the IAI. The content of this document has to be certified by the IAI before becoming part of an official IFC Model View Definition.					

Figure 16: An example of the template for a IFC concept description, adopted from (NBIMS, 2007)

Table 18: A description of an IFC concept document -- adopted from (NBIMS, 2007)

Field	Description
Title	The name of the concept.
Reference	The code of the concept.
Relationships	The name of the entity in the concept.
Version	The sequential version number of the concept.
Status	The status of the EM, including sample, draft, final or deprecated.
History	The version history of the concept.
Authors	The names of the authors or editors of the concept.
Document Owner	The name of the person or organization responsible for updating the document.
Description	The description of the concept, i.e., usage in view definition diagram, instantiation diagram, and implementation diagram
Example	An example associated with the concept from Part 21 file.

Step 4: Testing and Validating the Constructability Exchange Model

The last step in creating an EM is testing and validation against the requirements of building projects (Nawari, 2012). To validate the constructability EM, we used version 10.4 of the IfcDoc application, which is an open source tool developed by buildingSMART for creating model view definitions to describe exchange requirements using IFC (buildingSMART, 2015b). The IfcDoc application supports rule-checking features for executing rules or implementation agreements on different entities, attributes, relations, and data types in IFC interfaces (Lee, 2015). Figure 17 displays the process of the constructability EM development and its validation. IfcDoc is a powerful debugging tool that enables us to validate the defined relations and rules within the concepts relevant to the BCAEM. In this study, the term BCAEM is used interchangeably with constructability EM.

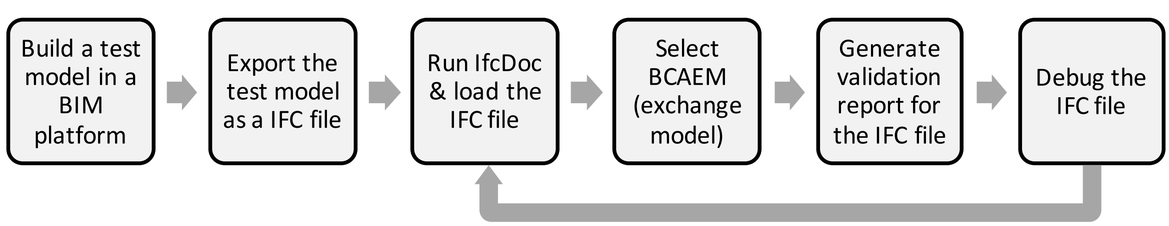


Figure 17: The validation process of EM using IfcDoc

Constructability Assessment Exchange Model

This section presents the results of developing constructability assessment exchange model.

Results of Step 1: Creating the Process Map of Information Exchange

Figure 18 shows the process map for implementing the constructability assessment in construction projects where designers are responsible for reviewing the constructability of their preliminary design in both the preliminary and design development phases. Designers can use the BCAEM to extract the subset of the model for the constructability assessment and can document the results of the constructability review to enhance the constructability of their designs. Moreover, designers can use BCAEM to deliver essential constructability information to contractors for their review; then, the contractors can send documents pertaining to the constructability review back to the designers.

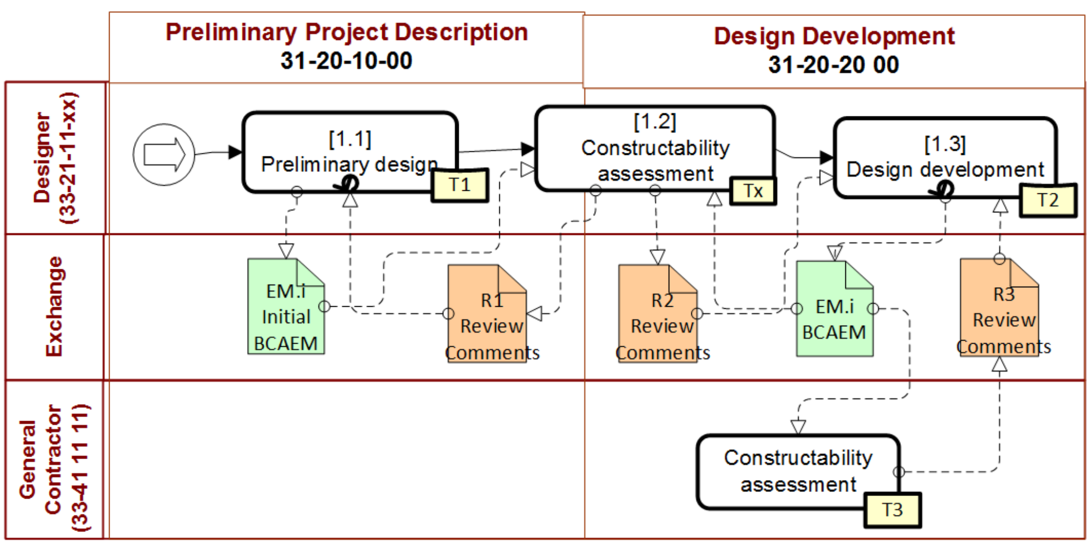


Figure 18: Process map of BCAEM

The purpose of the exchange requirements is to support coordination between designers, engineers, and construction managers for the constructability assessment of designs. Table 19 presents the description of the constructability assessment task represented in the BPMN diagram. In addition, Table 20 shows who sends or receives information pertaining to the constructability assessment task within the design processes. As shown in the table, the information will be exchanged between architects, engineers, and contractors. It also provides a generic description and outlines the typical content of the constructability EM.

Table 19: Constructability assessment

Type	Task
Name	Constructability assessment
Omniclass Code	31-20-20 00 Design Development
Documentation	Designers, engineers, and contractors can review the constructability of designs.

Table 20: Constructability exchange model

Project Stage	31-20-20 00 Design Development
Exchange Disciplines	From: (33-21-11-00) Architecture (33-21 31 00) Engineering To: (33-41 11 11) General Contracting
Description	It is based on the architectural and engineering designs. It provides the required details of building design models for assessing the constructability level of designs. It includes information about the major building components (structural frames, slabs, internal walls, external walls, roof, and staircase) and their construction types.
Related Exchange Models	Depending on MVDs, it can be exchange models relevant to a structural design and an architectural design exchange models.

Results of Step 2: Defining the Constructability Exchange Requirements and Rules

This study developed the constructability-IDM to document the requirements and the level of detail needed to set up BIM models for the constructability EM. Table 21 provides the detailed specifications and information of the EM for the constructability assessment. In addition, Appendix D represents the detailed specifications of the constructability exchange model. It specifies the users' needs for the constructability assessment and the method for translating these requirements by EM into computer-implementable code in the next step.

Table 21: The specifications of the constructability exchange model

Objects	Information Needed	Data Type	Required/ Optional
Columns, Beams, Slabs, Internal Walls, External Walls, Roof, and Staircase	Type	*String*	*R*
	Location	--	*R*
	Manufacturer	*String*	*O*
	Size	*Decimal*	*R*
	Area	*Decimal*	*R*
	Volume	*Decimal*	*R*
	Material	*String*	*R*
	Construction type	*String*	*R*
	Color	*String*	*O*
	Geometry	--	*R*
	Grid	--	*R*
	Opening size	*Decimal*	*R*
	Approval	*String*	*O*
	Actor	*String*	*O*

Results of Step 3: Modularizing the Exchange Requirements into IFC

The various components of the constructability-IDM discussed in the last step can serve as the functional requirements for the constructability exchange specification (BCAEM) to translate the requirements into computer codes. Based on the information requirements listed in the constructability-IDM, we created a BCAEM with thirty-five concepts, including seven new concepts and twenty-eight adopted or reused concepts from the PCI MVD and the the Building Lifecycle Interoperable Software (BLIS) (Table 22). Each concept includes its relevant IFC binding diagrams identifying the IFC entities and their references to each other (Appendix E). For example, the "CMC-02: Slab construction type properties" concept is about construction systems of slab elements and should include only the name of the construction system and not the name of the material, density, or weight (see Table 23). Figure 19 demonstrates a document for this concept, which includes an IFC binding diagram and a list of attributes for each entity to indicate the assignments or rules that might apply in the concept's implementation. The concept document also includes an example of the IFC Part-21 instance file associated to a slab element.

Table 22: The list of concepts in the BCAEM

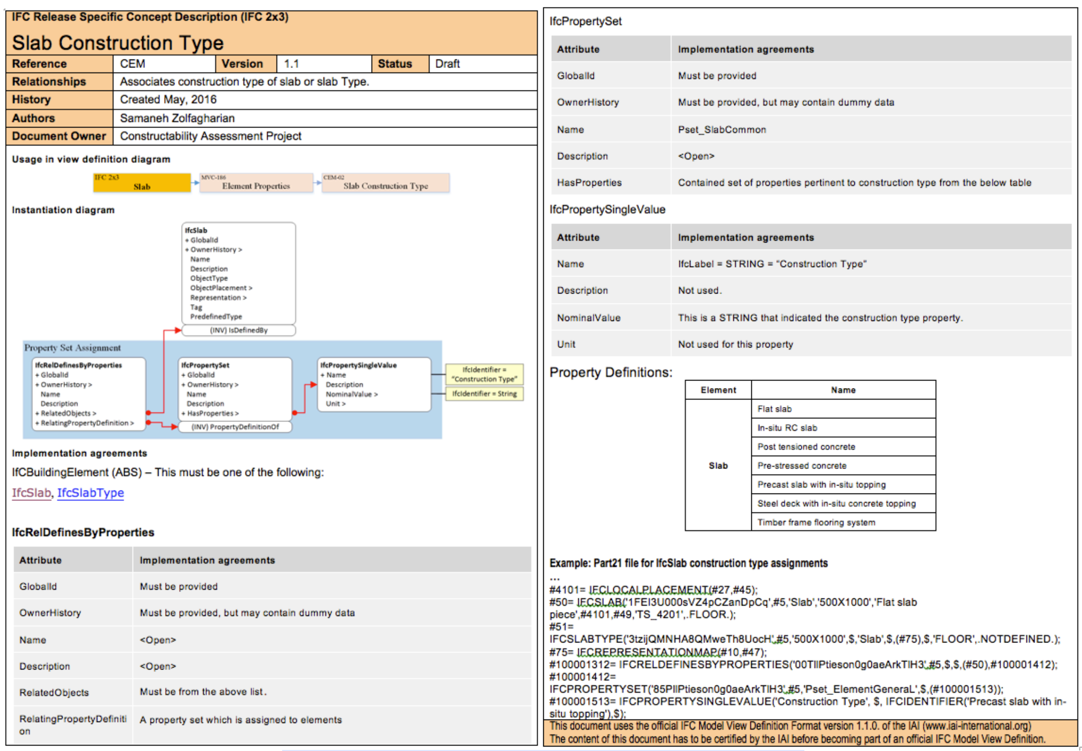
Source	BCAEM Concepts
New	CMC-01: Structural construction type properties
New	CMC-02: Slab construction type properties
New	CMC-03: Wall construction type properties
New	CMC-05: Roof construction type properties
New	CMC-06: Staircase construction type properties
New	CMC-07: Element quantities-I
New	CMC-08: Element quantities-II
Reused	CMC-09: Element Opening assignment
Adopted	CMC-011: Building element aggregation
Reused	CMC-012: Site contained in project

Table 22: The list of concepts in the BCAEM (continued)

Source	BCAEM Concepts
Reused	CMC-013: Building contained in site
Reused	CMC-014: Building story contained in building
Reused	CMC-015: Grid name
Reused	CMC-016: Grid representation
Reused	CMC-017: Grid axis assignment
Reused	CMC-018: Object placement relative to grid
Reused	CMC-019: Building element attributes
Reused	CMC-020: Building element type assignment
Reused	CMC-022: Assignment of approval
Reused	CMC-023: Assignment of actor
Adopted	CMC-024: Associate material to piece
Reused	CMC-025: Building element assignment to spatial structure
Reused	CMC-026: Placement of pieces to building element
Reused	CMC-027: Absolute placement of building element
Reused	CMC-029: Extrude shape geometry
Reused	CMC-036: Generic bounded surface geometry
Reused	CMC-037: Library association
Reused	MVC-581: Root attributes
Reused	MVD-582: Generic geometric representation
Reused	MVC-880: Site attributes
Reused	MVC-888: Metric project units
Reused	MVC-889: Imperial project units
Reused	MVC-890: Project name
Reused	MVC-893: Building attributes
Reused	MVC-895: Building story attributes

Table 23: A part of the model exchange requirements for a structural slab (CEM02)

Component	Attribute name	Description
Slab	Thickness	Thickness of the slab
	Area	Area of the slab, assuming dimensions are fixed along the slab axis
	Construction systems	Name of the construction systems of the slab



IFC Release Specific Concept Description (IFC 2x3)

Slab Construction Type

Reference	CEM	Version	1.1	Status	Draft
Relationships	Associates construction type of slab or slab Type.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project				

Usage in view definition diagram

Instantiation diagram

Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcSlab, IfcSlabType

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_SlabCommon
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

Attribute	Implementation agreements
Name	IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

Element	Name
Slab	Flat slab
	In-situ RC slab
	Post tensioned concrete
	Pre-stressed concrete
	Precast slab with in-situ topping
	Steel deck with in-situ concrete topping
	Timber frame flooring system

Example: Part21 file for IfcSlab construction type assignments

```
...
#4101= IFCLOCALPLACEMENT(#27,#45);
#50= IFCSLAB('1FEI3U000sVZ4pCZanDpCq',#5,'Slab','500X1000','Flat slab piece',#4101,#49,'TS_4201',.FLOOR.);
#51=
IFCSLABTYPE('3tzijQMNHA8QMweTh8UocH',#5,'500X1000',$,'Slab',$,(#75),$,'FLOOR',.NOTDEFINED.);
#75= IFCREPRESENTATIONMAP(#10,#47);
#100001312= IFCRELDEFINESBYPROPERTIES('00TIIPtieson0g0aeArkTIH3',#5,$,$,(#50),#100001412);
#100001412=
IFCPROPERTYSET('85PIIPtieson0g0aeArkTIH3',#5,'Pset_ElementGeneraL',$,(#100001513));
#100001513= IFCPROPERTYSINGLEVALUE('Construction Type', $, IFCIDENTIFIER('Precast slab with in-situ topping'),$);
```

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The content of this document has to be certified by the IAI before becoming part of an official IFC Model View Definition.

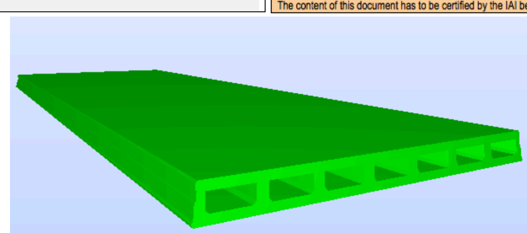


Figure 19: An IFC binding- concept CEM-02 Slab

Results of Step 4: Testing and Validating the Constructability Exchange Model

The last component of NBIMS is to validate the constructability EM and the semantics of the BCAEM implementation. In this study, we tested the concepts to validate how they will interface and not overlap when they are aggregated. Based on the proposed framework by NBIMS (2007), this research provided test cases for both import and export functions that cover the scope of the BIM data to be exchanged for the constructability assessment purpose. After defining related concepts to the BCAEM, we built concepts in the IfcDoc application and implemented defined rules associated with each concept. Then we created multiple IFC instance files for validation and debugging purposes using the IFC Release 2x3 baseline. By running the IfcDoc application, we were able to check different types of rules, such as data value, the existing or null value, global and local uniqueness, the correct type of entity or subtype entity, an instance only if a given condition is satisfied, the upper and lower bound on the number of attributes, a reference or inverse relationship, and syntax or the scope of a model view (Charles Eastman et al., 2014). Figure 20 displays the overall process of the validation through IfcDoc for a BIM model test case. After creating test cases for the EM, we can pass the model to software companies so they can implement test cases for related concepts and validate the data import/export functions in their IFC translators. The BCAEM can be added to other MVDs such as PCI-MVD or AISC-MVD for the purpose of the constructability assessment and review.

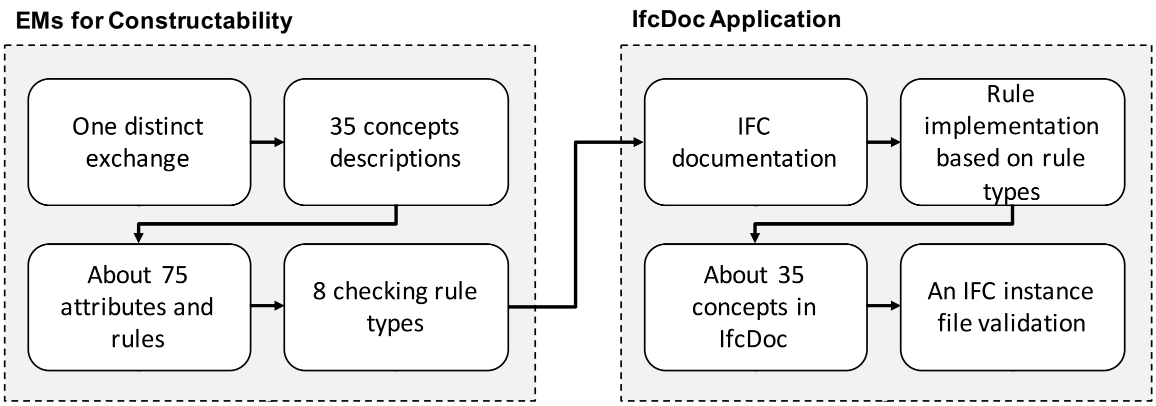


Figure 20: BCAEM rules and implementation on the IfcDoc application

We created the BCAEM exchange under "Scope" (Figure 21) and BCAEM's concepts under "Fundamental concepts and assumptions" in the IfcDoc application (Figure 22).

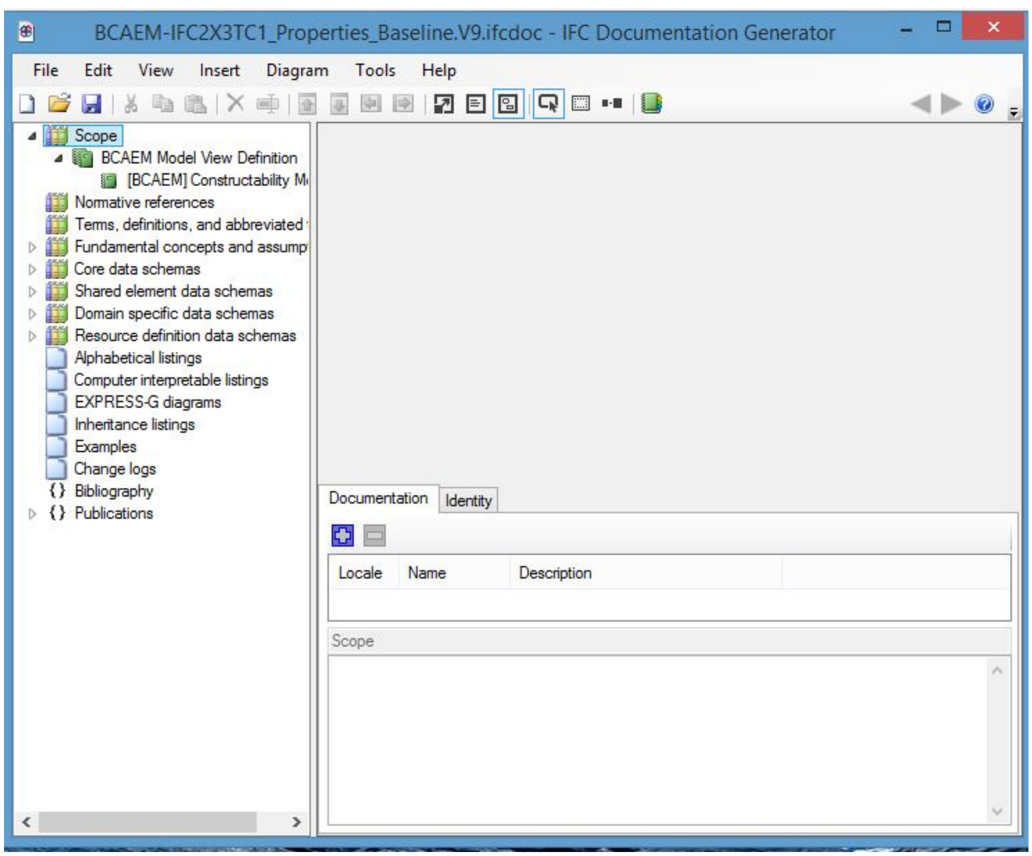


Figure 21: A screenshot to create the exchange model (BCAEM)

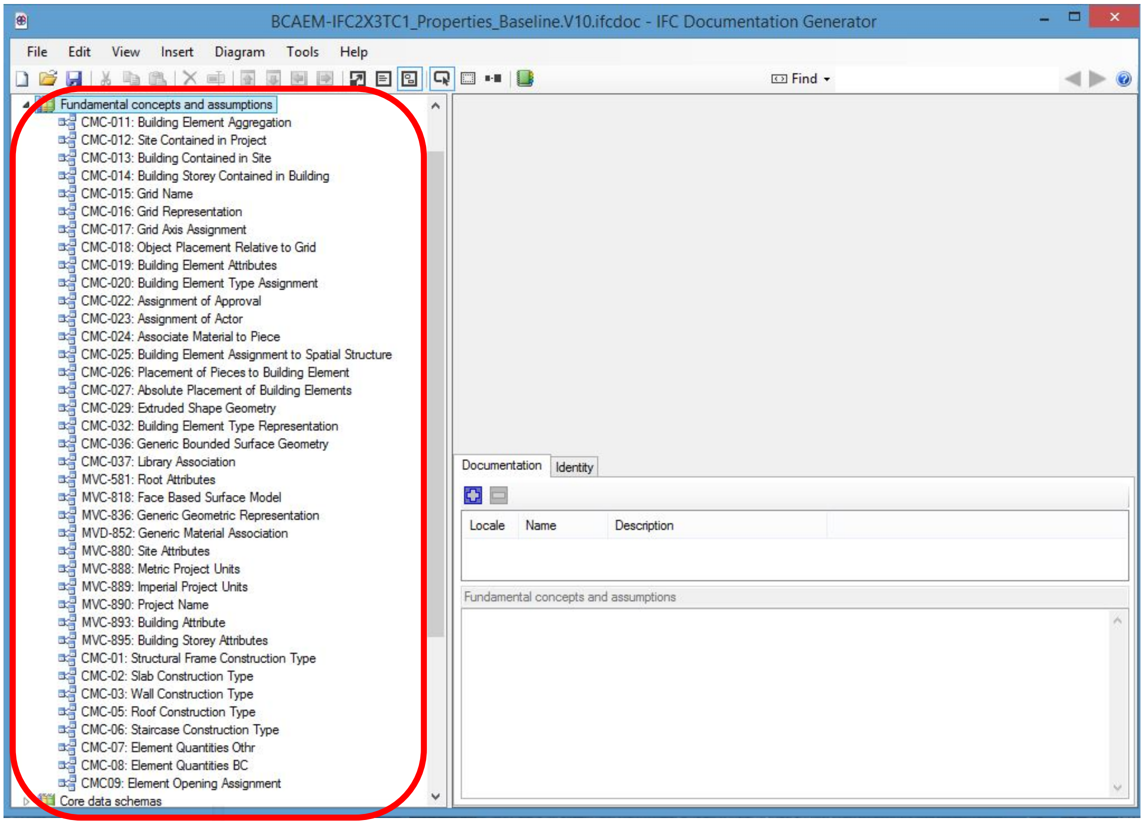


Figure 22: A list of the concept relevant to the BCAEM in IfcDoc

Each concept in the BCAEM provides detailed specifications and contains a definition, an instantiation diagram of IFC bindings, and implementation guidance for software developers. As displayed in Figure 23 and Figure 24, the IFC bindings and implementation guidance for each concept should be mapped into the IfcDoc application. We created IFC bindings demonstrating the relational structure of the concept under the “Template” tab and implementation rules describing some predefined values and rules (e.g., condition rules and logic operators “AND” and “OR”) under the “Operations” tab in the IfcDoc application.

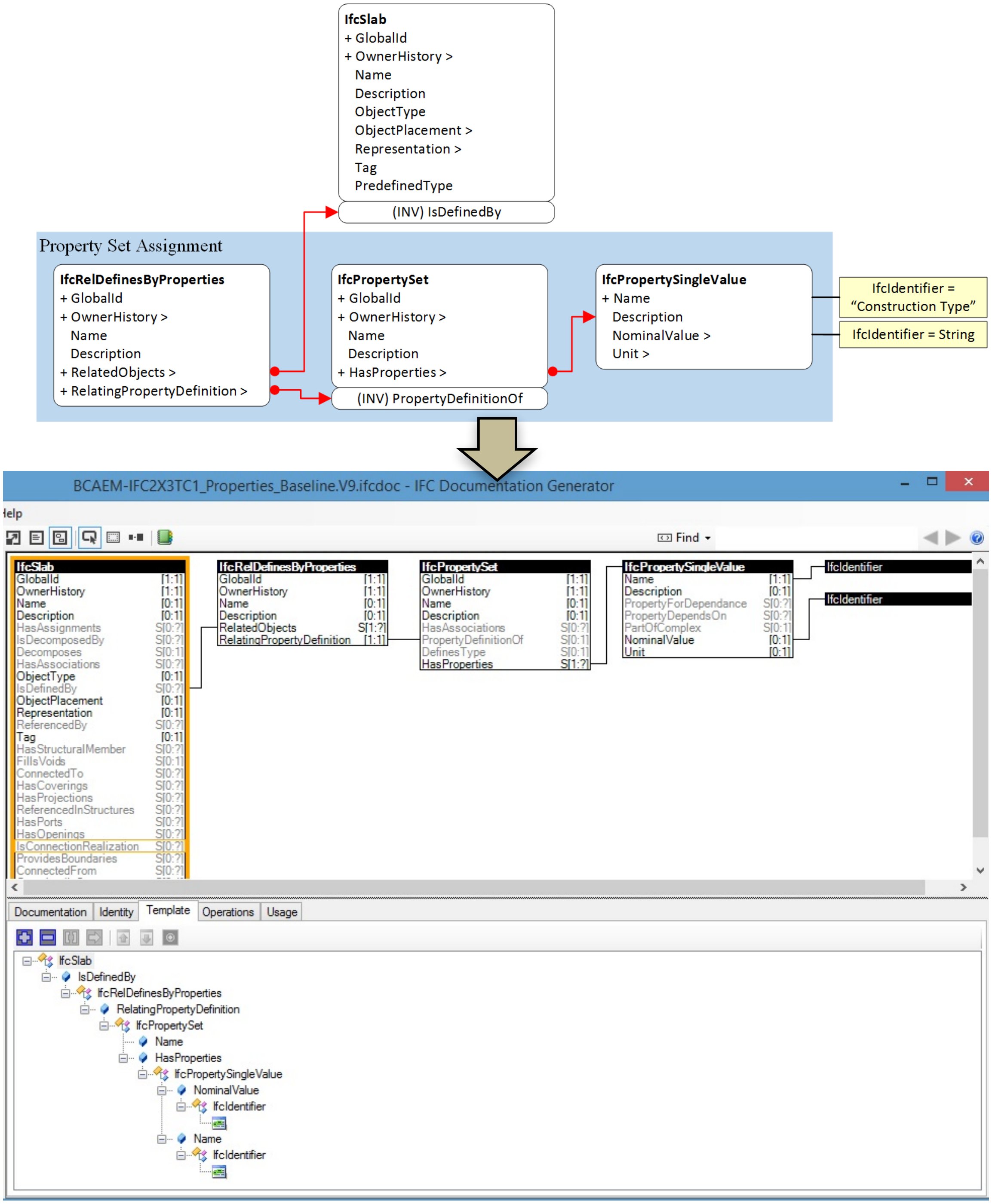


Figure 23: Mapping IFC binding diagram into IfcDoc

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

Attribute	Implementation agreements
Name	IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

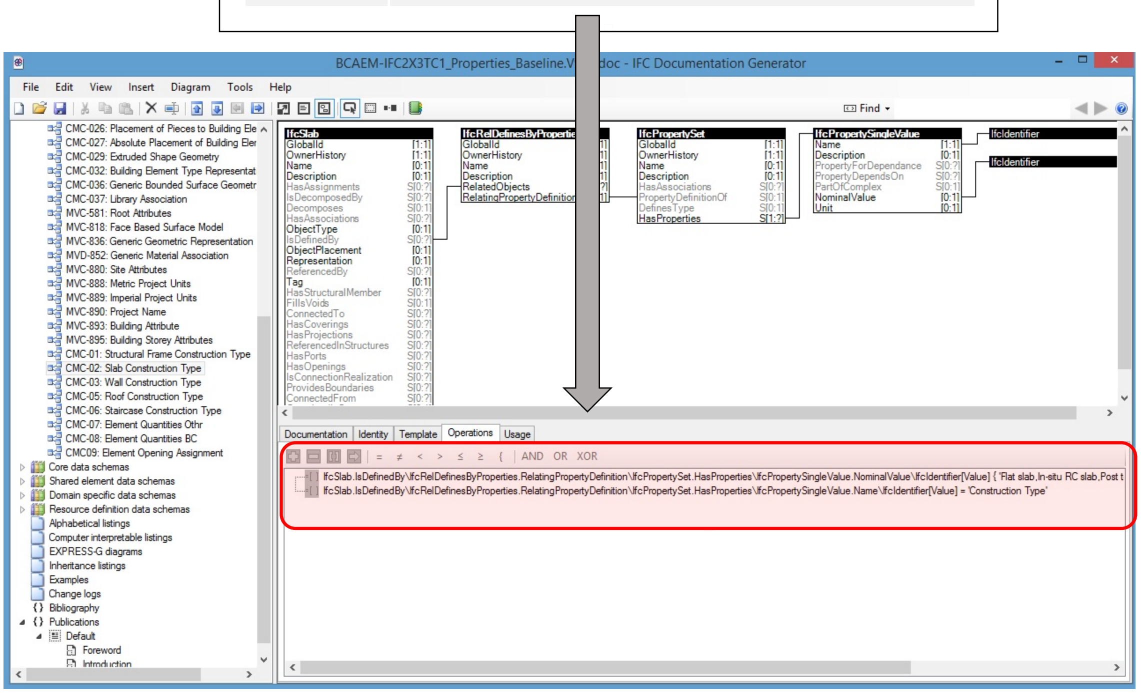


Figure 24: Mapping implementation rules into the IfcDoc application

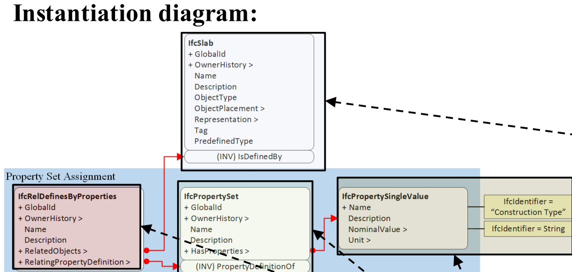
Validation Reports and Evaluations in the IfcDoc Application

For validation purposes, we created several comprehensive models that tested a large number of concepts and also simple models that tested only a single or several concepts. We manually created text-based instance models in the IFC format due to a lack of available IFC translators for the BCAEM. These test models were designed to satisfy all of the concepts and predefined rules in the constructability EM. Thus, we created all entities and object instances within a Part-21 test model based on defined rules and relations within the concepts (see Table 24). The test models consisted of object instances such as beams, walls, and slab elements. The aim of developing the test models was to check every concept and combination of concepts in the constructability EM thoroughly. Besides verifying a number of concepts in the test models, we ensured that the rules do not have any conflicts by validating all of the test models against various sets of conditions to eliminate all logical errors.

Table 24: An example of mapping a concept to create an instance object

CEM-02 Slab Construction Type	Part #21

Instantiation diagram:



Implementation agreements:

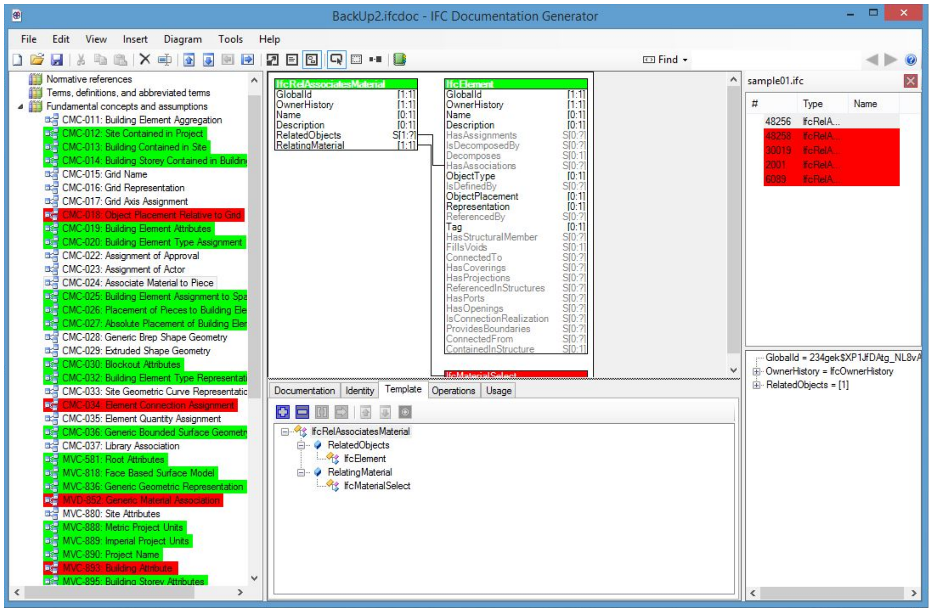
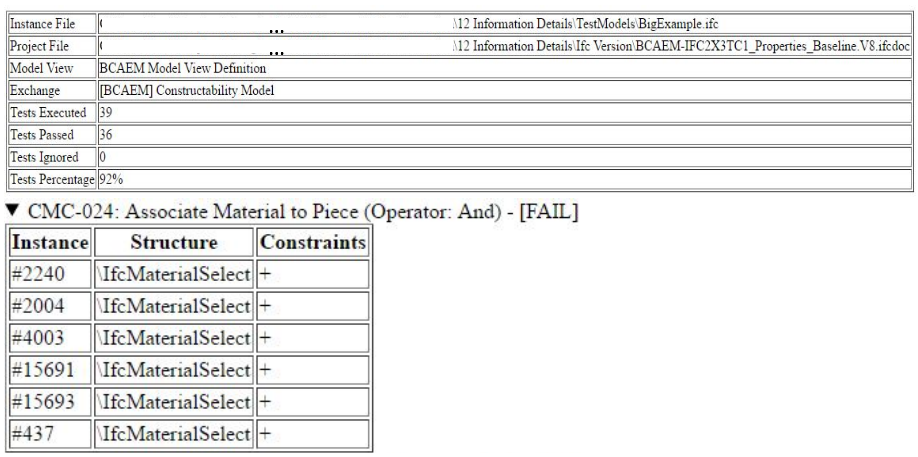
Attribute	Implementation agreements
Name	Must be IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	Must be a STRING that indicated the construction type property.
Unit	Not used for this property

Element	Name
Slab	Flat slab
	In-situ RC slab
	Post tensioned concrete
	Pre-stressed concrete
	Precast slab with in-situ topping
	Steel deck with in-situ concrete topping
	Timber frame flooring system

```
#4101= IFCLOCALPLACEMENT(#27,#45);
#50=
IFCSLAB('1FEI3U000sVZ4pCZanDpCq',#5,'Slab','50
0X1000','Flat slab
piece',#4101,#49,'TS_4201',.FLOOR.);
#51=
IFCSLABTYPE('3tzijQMNHA8QMweTh8UocH',#5,'5
00X1000',$,'Slab',$,(#75),$,'FLOOR',.NOTDEFINED.
);
#75= IFCREPRESENTATIONMAP(#10,#47);
#100001312=
IFCRELDEFINESBYPROPERTIES('00TIlPtieson0g0
aeArkTIH3',#5,$,$,(#50),#100001412);
#100001412=
IFCPROPERTYSET('85PIlPtieson0g0aeArkTIH3',#5,'
Pset_ElementGeneraL',$,(#100001513));
#100001513=
IFCPROPERTYSINGLEVALUE('Construction Type',
$, IFCIDENTIFIER('Precast slab with in-situ
topping'),$);
```

Thus, we validated the test models to ensure that they accurately implemented all of the rules, values, and relationships. For validation purposes, the IfcDoc application automatically generates a validation report on the user interface or in an HTML format (Table 25). Any error during validation can be attributed to an anomaly in either the test model or the logical rules. In the user interface of the IfcDoc application, green highlights on the text signifies that the entities, attributes, and relations passed the validation process, so the test model complies with the constructability EM specification. In contrast, the text highlighted in red shows failures and invalid entities, attributes, or relations. In the HTML format, "Test Percentage" shows the percentage of passed concepts. If any error occurs in an instance of a concept, the concept will be tagged as failed in the validation report. In addition, the report shows which of the instances failed and why. For example, in the HTML report at Table 25, "IfcMaterialSelect" under the Structure column shows this attribute is missing in the test model. The plus sign (+) under "constraints" also illustrates that the value of the attribute of an instance is defined based on the concept definition.

Table 25: Examples of validation reports generated by the IfcDoc application

Report Format	Example
Color-coded report for one instance	
HTML report for one instance	

Instance File	(... \12 Information Details\TestModels\BigExample.ifc
Project File	(... \12 Information Details\Ifc Version\BCAEM-IFC2X3TC1_Properties_Baseline.V8.ifcdoc
Model View	BCAEM Model View Definition
Exchange	[BCAEM] Constructability Model
Tests Executed	39
Tests Passed	36
Tests Ignored	0
Tests Percentage	92%

▼ CMC-024: Associate Material to Piece (Operator: And) - [FAIL]

Instance	Structure	Constraints
#2240	\IfcMaterialSelect	+
#2004	\IfcMaterialSelect	+
#4003	\IfcMaterialSelect	+
#15691	\IfcMaterialSelect	+
#15693	\IfcMaterialSelect	+
#437	\IfcMaterialSelect	+

We created a two-story building as a test model that includes beam, columns, and slabs (Figure 25), as well as a wall instance and a slab instance to validate the constructability EM. The part-21 file of the slab test model is available in Appendix F. We evaluated the test model using the IfcDoc application according to the BCAEM in order to identify the cause of any errors. Based on the validation reports, we found that several errors occurred during the validation process, and we debugged them before finalizing the constructability EM to be used by software developers in the future. Debugging necessitated some changes in the definition of the concepts, rules, or IFC bindings.

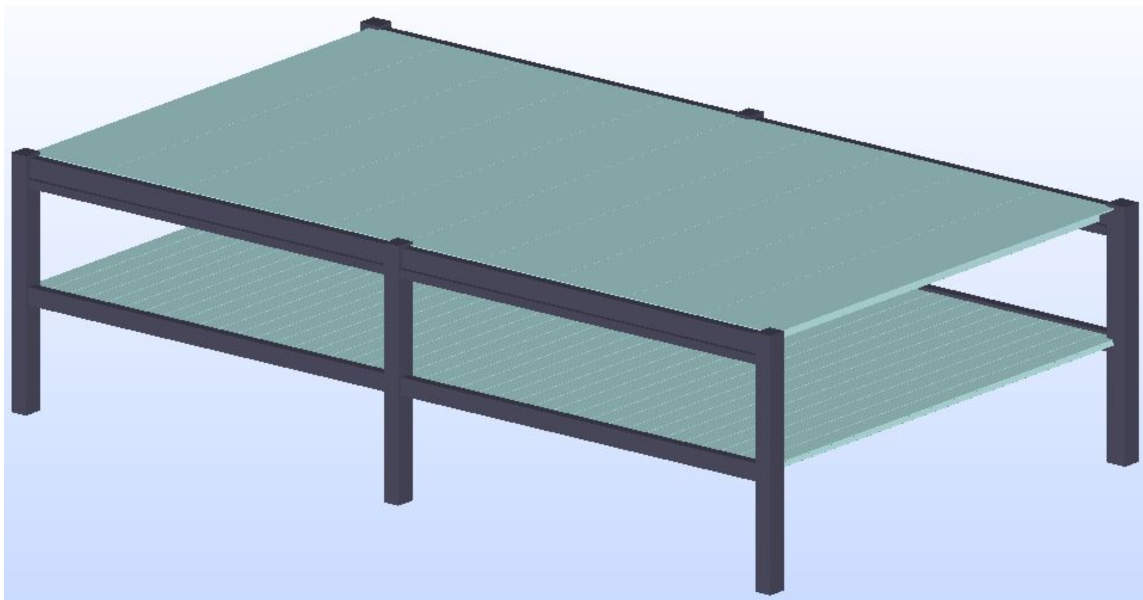
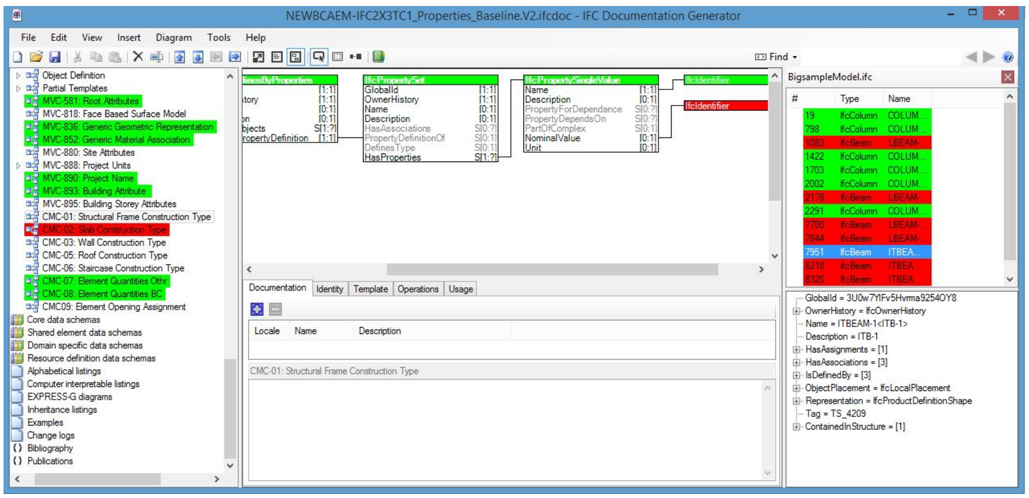


Figure 25: A two story test model

Instance of Slab

#10000200= IFCRELDEFINESBYPROPERTIES('1reb3E4DSH0JEPQKKHBXURB',#8641,$,$,(#1083,#2178,#7700,#7844,#7951,#8218,#8325,#8432),#10000210);
#10000210= IFCPROPERTYSET('2reb3E4DSH0JEPQKKHBXURB',#8641,'General Properties',$,(#10000220));
#10000220= IFCPROPERTYSINGLEVALUE($, $,$,$);

UI Report



HTML Report

IfcBeam (8)

▼ CMC-01: Structural Frame Construction Type (Operator: And) - [FAIL]

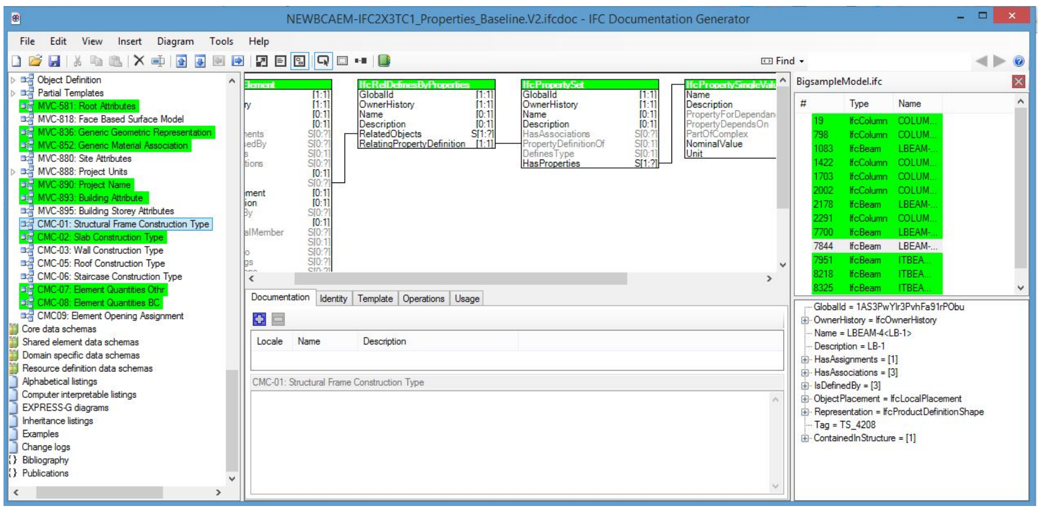
Instance	Structure	Constraints
#1083	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#2178	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#7700	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#7844	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#7951	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#8218	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#8325	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'
#8432	+	IfcBuildingElement.IsDefinedBy\IfcRelDefinesByProperties.RelatingPropertyDefinition\IfcPropertySet.HasProperties\IfcPropertySingleValue.NominalValue\IfcIdentifier[Value] { 'Cast in-situ RC frame,In-situ loadbearing wall,Masonry,Metal stud frame,Post-tensioning structure,Pre-engineered metal building,Pre-tensioning structure,Precast concrete frame,Steel encased in concrete,Structural steel with fire proofing,Timber structural frame'

Figure 26: Errors in construction type- missing attributes in the Part-21 test model

Instance of Slab

#10000200=
IFCRELDEFINESBYPROPERTIES('1reb3E4DSH0JEPQKKHBXURB',#8641,$,$,(#1083,#2178,#7700,#7844,#7951,#8218,#8325,#8432),#10000210);
#10000210= IFCPROPERTYSET('2reb3E4DSH0JEPQKKHBXURB',#8641,'General Properties',$,(#10000220));
#10000220= IFCPROPERTYSINGLEVALUE('Construction Type', $, IFCIDENTIFIER('Light weight brick'),$);

UI Report



HTML Report

IfcBeam (8)

▼ CMC-01: Structural Frame Construction Type (Operator: And)

Instance	Structure	Constraints
#1083	+	+
#2178	+	+
#7700	+	+
#7844	+	+
#7951	+	+
#8218	+	+
#8325	+	+
#8432	+	+

Figure 27: Debugging the errors in the Part-21 test model

Figure 26 displays examples of errors in the test model. The validation report shows that some instances in the test model include an invalid data type of the NominalValue attribute of IFCPROPERTYSINGLEVALUE. In addition, the “Name” attribute should be “Construction Type,” which is a missing value of an attribute in the instance. Because the validation reports displayed these errors and their locations, we could easily debug any problems. After fixing them, we evaluated the test model again, and the report of validation shows that all rules and conditions were satisfied by the test model as shown in Figure 27.

Summary

IFC is the most popular exchange format among construction disciplines. An IFC model provides information about objects, processes, and relationships for sharing among the disciplines of architecture, engineering, and construction (AEC) during a project’s lifecycle. However, such IFC models are big and have some redundancies, especially in large and complex projects. Thus, designers have difficulty in identifying whether a design model has all the required information for a specific task or purpose (Lee, 2015, Venugopal et al., 2012). To solve the redundancy issue and to enhance the interoperability process, AEC professionals need EMs and MVDs that enable them to define a required subset of IFC schema for a specific purpose or project (buildingSMART, 2015c). This study created an EM that has all the required information for the constructability assessment of designs. We mapped and modularized the constructability exchange requirements into IFC and validated it using the IfcDoc application so that software vendors can use the EM to examine whether their IFC translators comply with terminologies and rule sets defined in BCAEM. They also can use it to debug their IFC translators based on validation reports generated by the IfcDoc application. Further, AEC professionals can also use the EM to validate their models during the design phase to ensure the models have all the information required for the constructability assessment of designs.

CHAPTER 6

VALIDATION

The goal of the validation was to examine the overall application of the BCAEM in commercial construction projects. The hypotheses of the validation seek to examine if the integration of construction knowledge into the design stage via BCAEM would help designers with:

1. Exploring the constructability of designs in less time;
2. Assessing the constructability of designs more accurately; and
3. Formalizing the method of constructability assessment.

To test these hypotheses, we had the option of conducting either a case study or an experimental study. Since results captured from an experimental study are more robust, legitimate, and generalizable compared to the results from a case study (Gable, 1994, Liu et al., 2014), we selected an experimental study to validate the application of the BCAEM. The validation plan is explained in the following section.

Experiment Design

This section describes the test method, tasks, equipment, data collection plan, and participants.

Test method

We implemented the Wizard of Oz technique, which simulates the responses of the system and provides results for the participants. The main reason for choosing this technique was a lack of IFC translators that implement EMs or any model view definitions in current BIM platforms. We chose to run a "one-on-one" test, meaning each participant attended the experiment session individually in order to eliminate subject-to-subject variation. The experiment was based on a within-subject design in which all participants completed the same tasks. The within-subject design has a potential transfer of learning effects, which means that by performing one task, participants may learn how to complete the tasks that follow (Hackos et al., 1995). To mitigate this problem, we used the counterbalancing technique to randomize and vary the order of the tasks (Hackos et al., 1995). The randomized sequence was selected before running the experiment as presented in Table 26.

Table 26: Randomizing the sequence of reviewing designs

Subject	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**
Design	A B C	B C A	C A B	A B C	C B A	B C A	A C B	C B A

Data Collection Plan

To evaluate our hypotheses, we conducted an exploratory study and comparison test, capturing both performance and preference data during the experiment, adopted from Hackos et al., (1995). The performance data included constructability scores and the time to complete each task. The preference data included the participants' feelings and opinions about the BCAEM and the ease of conducting the constructability assessment using it.

Tasks

We designed a short demographic questionnaire to capture information regarding the participants' current job, level of education, and years of experience in commercial building construction, and we asked them to complete the questionnaire prior to conducting the experiment. To run the experiment, we selected three school designs – Designs A, B, and C. Design A was a semi-complete design, Design B was an incomplete design, and Design C was a complete design (Figure 28). The first task for the participants was to rate the constructability of each of these designs on a scale of 1 to100. The goal of this task was to capture how designers think about the constructability of designs. In the second task, we asked designers to improve the constructability of Design A in an attempt gain insight about how designers think about constructability improvements in their designs.

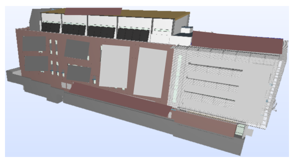
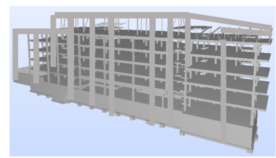
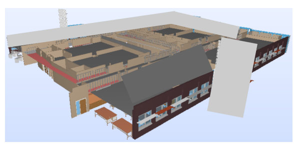
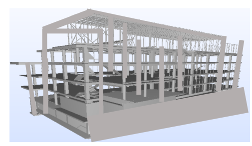
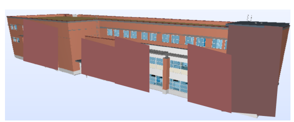
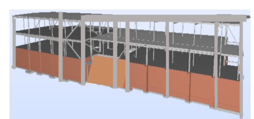
#	Architectural Designs	Structural Designs
Design A		
Design B		
Design C		

Figure 28: Structural and architectural design alternatives

After the completion of Task 2, we decided to provide a summary of the study's proposed constructability assessment model so that the participants could have a better understanding of it prior to performing the next task. We also decided to explain how the BCAEM could work (the Wizard of Oz technique) if it was implemented in BIM platforms (Figure 29). In Task 3, we asked designers to use the BCAEM for calculating the constructability of the designs. To facilitate this task, we created an interface that simulates the BCAEM's implementation in a BIM platform (Figure 30), with the goal of examining the effectiveness of using the BCAEM for measuring the constructability of designs.

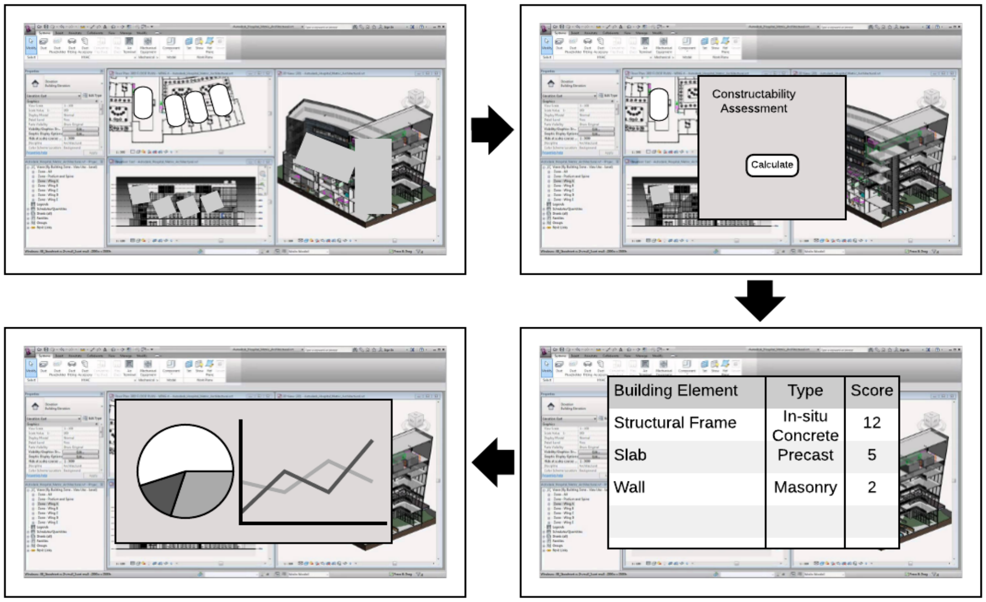


Figure 29: Wizard of Oz-BCAEM

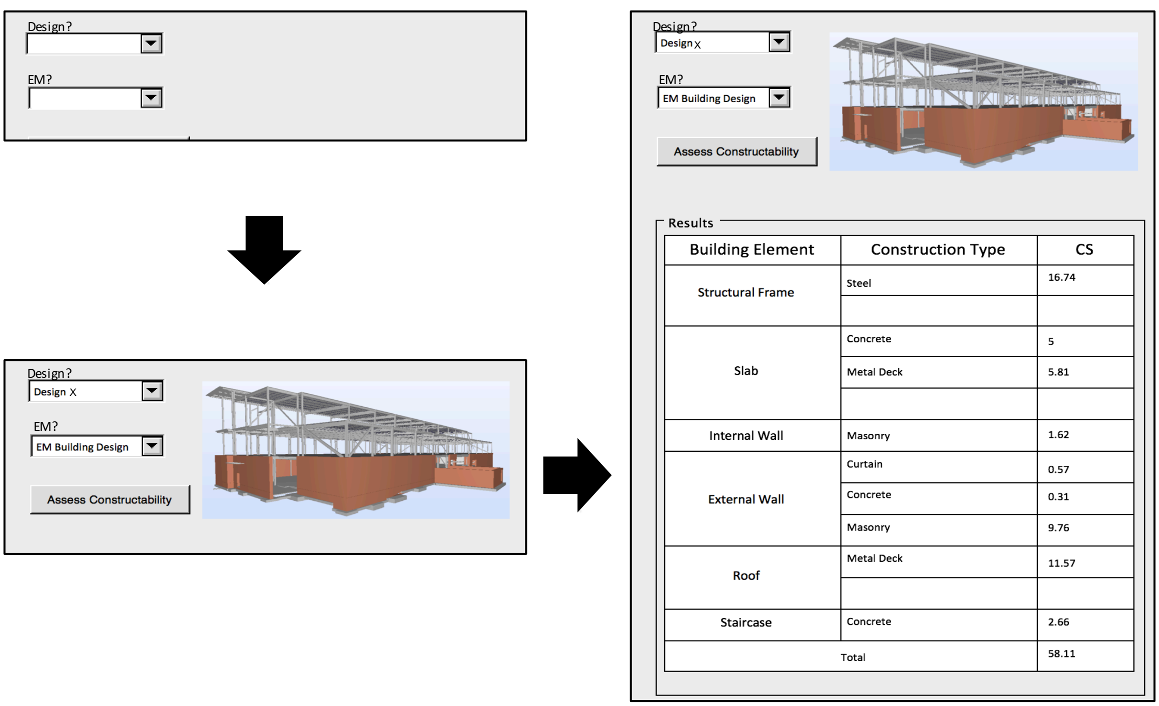


Figure 30: BCAEM interface

In Task 4, we asked the participants to fill out a post-experiment questionnaire. Appendix G is a paper format of the questionnaire. The goal of this task was to capture the participants' feedback and comments about the application of the BCAEM in commercial building projects. Figure 31 presents a summary of the processes and tasks of the experiment.

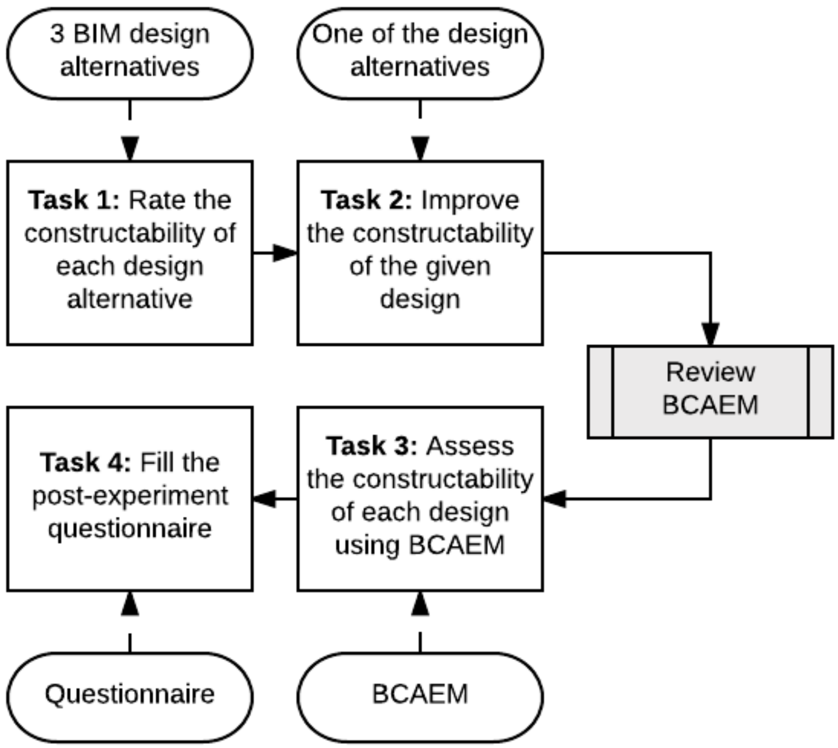


Figure 31: The process and tasks of the experiment

Test Equipment

We used a MacBook Pro (15-inch display, 2.5GHz Intel Core i7 CPU, 16 GB 1600 MHz DDR3 RAM, and with Intel Iris Pro 1536 MB Graphics) to run all of the interviews.

Consent Form

Before starting the experiment, we gave the participants a consent form to read and sign before agreeing to participate in the experiment. The consent form also informed them about the survey procedures, benefits, and compensation. The IRB reviewed the study protocol and approved it in advance.

Experimental Study

We asked the participants to think aloud while performing the tasks so that we could note all their critical comments or concerns. We also used a digital voice recorder during the experiment sessions to create a set of audio recordings for back up. We introduced the goal of the experiment sessions, conducted a short demographic survey, and then walked the participants through the experiment's tasks. The experiment sessions were semi-structured and exploratory, so we asked follow-up questions whenever needed to clarify the responses and behavior of the participants.

Pilot Study

We conducted a pilot study with two subjects to ensure the quality of the experiment, tasks, and questions and to determine if we needed to revise any part of the experiment or questions. Then, based on the received feedback, we modified and improved the experiment.

Participants

We conducted the experiment in San Francisco, California. According to Hackos et al., (1995), most usability findings are usually the same (about 80 percent) across different locations, so implementing the survey in one location is fine. Before selecting the participants for the experiment, we checked their LinkedIn profiles to determine whether they were designers and used the screening questionnaire to determine if they had ever worked on commercial construction projects. If an individual met the criteria, we sent him or her an email to schedule an appointment and obtain consent to run the experiment. Since all of the participants were designers (from one category), four to five participants is enough for a sufficient sampling, (Hackos et al., 1995), and the number of participants in our study exceeded that minimum requirement.

Results of the Experimental Study

Eight participants who had worked in commercial construction projects, including universities, science and technology labs, schools, institutional buildings, warehouses, malls, restaurants, retail structures, high- or mid-rise offices, hospitals, airports, corporate buildings, and hotels, in California, Georgia, Hawaii, Maryland, and Missouri states attended the experimental study. Table 27 demonstrates the demographic information of these participants.

Table 27: Demographics of participants

Variables		**Percentage (%) (8 Subjects)**
Level of Education	Bachelor's	12%
	Master's	88%
Current position	Designers & BIM Specialists	63%
	Project Architect	13%
	Design Manager	13%
	Structural Eng.	13%
Years of experience in construction	1 to 5 years	13%
	6 to 10 years	38%
	More than 10 years	50%
Years of experience in commercial	1 to 5 years	13%
	6 to 10 years	38%
	More than 10 years	50%

Finding from Task 1: rating the constructability of the designs

Qualitative Results

In conducting Task 1, the subjects were not instructed as to whether they should review the architectural designs or the structural designs or both. One half of the participants reviewed both architectural and structural models, while the others analyzed only the architectural designs.

During the review, the participants described their constructability criteria. Six of the eight participants mentioned that the material for the exterior walls was an important criterion in their assessment, but only one person reviewed the material for the structural frame (Figure 32). The designers' focus on architectural components contrasts with the typical contractor's area of focus, which based on the constructability assessment model, would be structural frames, as they have the highest contribution rate to the constructability of a design. Moreover, surprisingly, almost 38% of the subjects reviewed furniture and casework and 63% checked space programs and space functionalities to assess constructability, despite the fact that space programs and space functionalities do not really contribute to the ease of a design's construction.

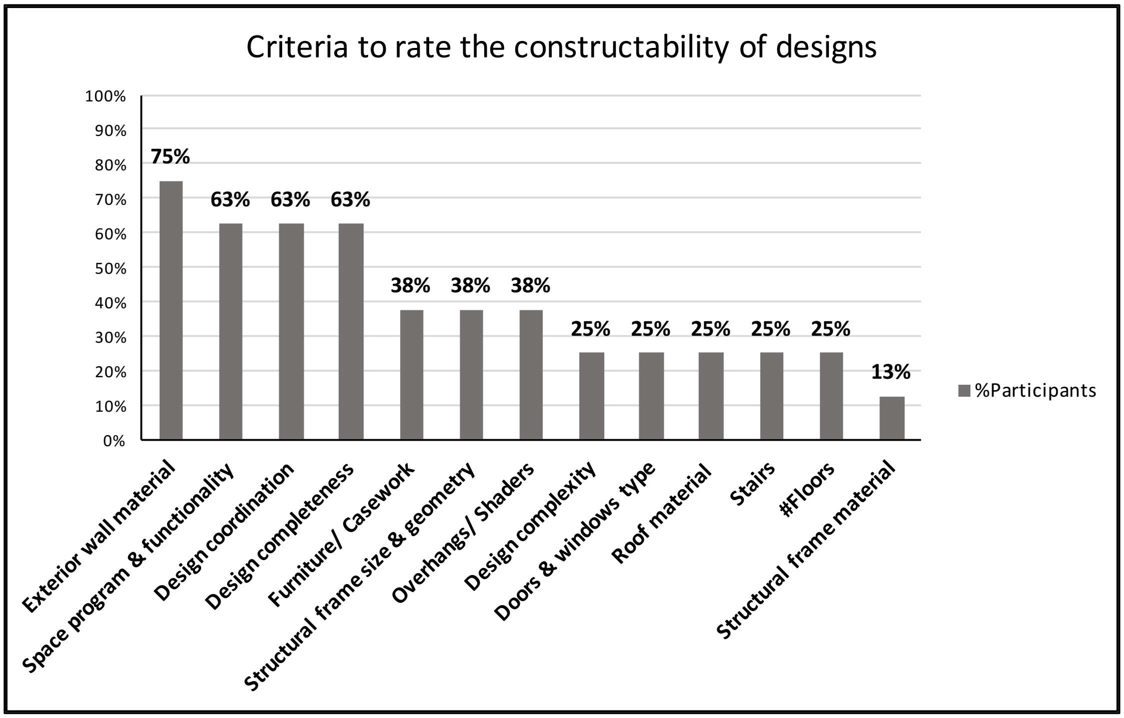


Figure 32: Participants' criteria to assess the constructability of designs

Quantitative Results

Design A has a combination of steel and concrete structures with a concrete and metal slab. The internal walls of Design A are masonry and the external walls are made of concrete and curtain wall. Design A also has steel decking roof with in-situ concrete slabs and a concrete staircase. Given the rationale presented in Figure 32 (e.g., exterior wall material, space program, and functionality), most of the designers gave Design A a very high score (Figure 33). The mean of the constructability score was 78.13, with a standard deviation of 12.98.

Design B is a combination of steel and concrete structure and a concrete slab. The internal walls of Design B are made of gypsum, metal stud, and masonry, while the external walls are comprised of concrete, masonry, and glass. Design B has a concrete staircase, but the model presents no information about the roof. The results of the constructability assessments show that the designers did not have a consistent opinion of

Design B. With a maximum score of 95 and a minimum of 20, Design B had an average rating of 64.38 and a standard deviation of 24.29.

Design C is a steel structure with a concrete and metal deck slab and internal walls are made of masonry. It also has external curtain, concrete, and masonry walls with a concrete staircase and metal stud roof. Most of the designers thought Design C was the most constructible. With a minimum of 60 and a maximum of 100, Design C had an average rating of 86.13 and a standard deviation of 12.05.

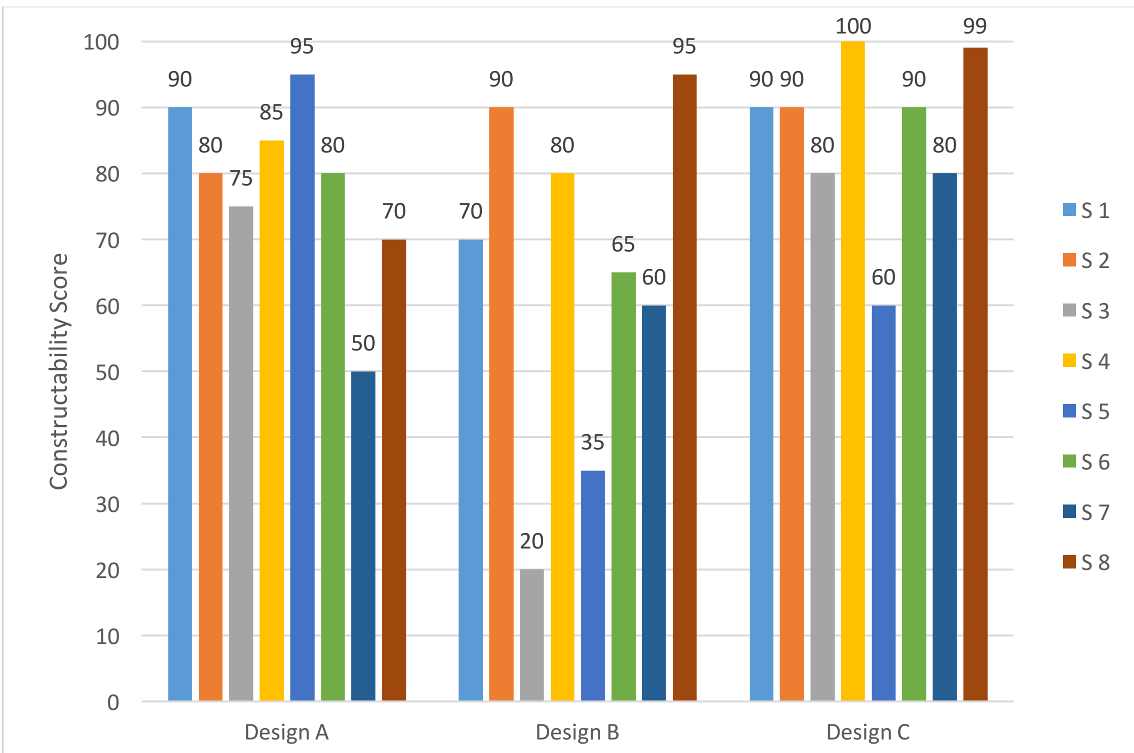


Figure 33: Constructability assessment of building designs

We also captured the time involved in performing Task 1. The time captured was the time that designers reviewed the designs and determined a constructability score. On average, Design A took 8:19 (i.e., eight minutes and 19 seconds), Design B took 7:10, and Design C took 6:35. The time captured is presented in detail in Figure 34.

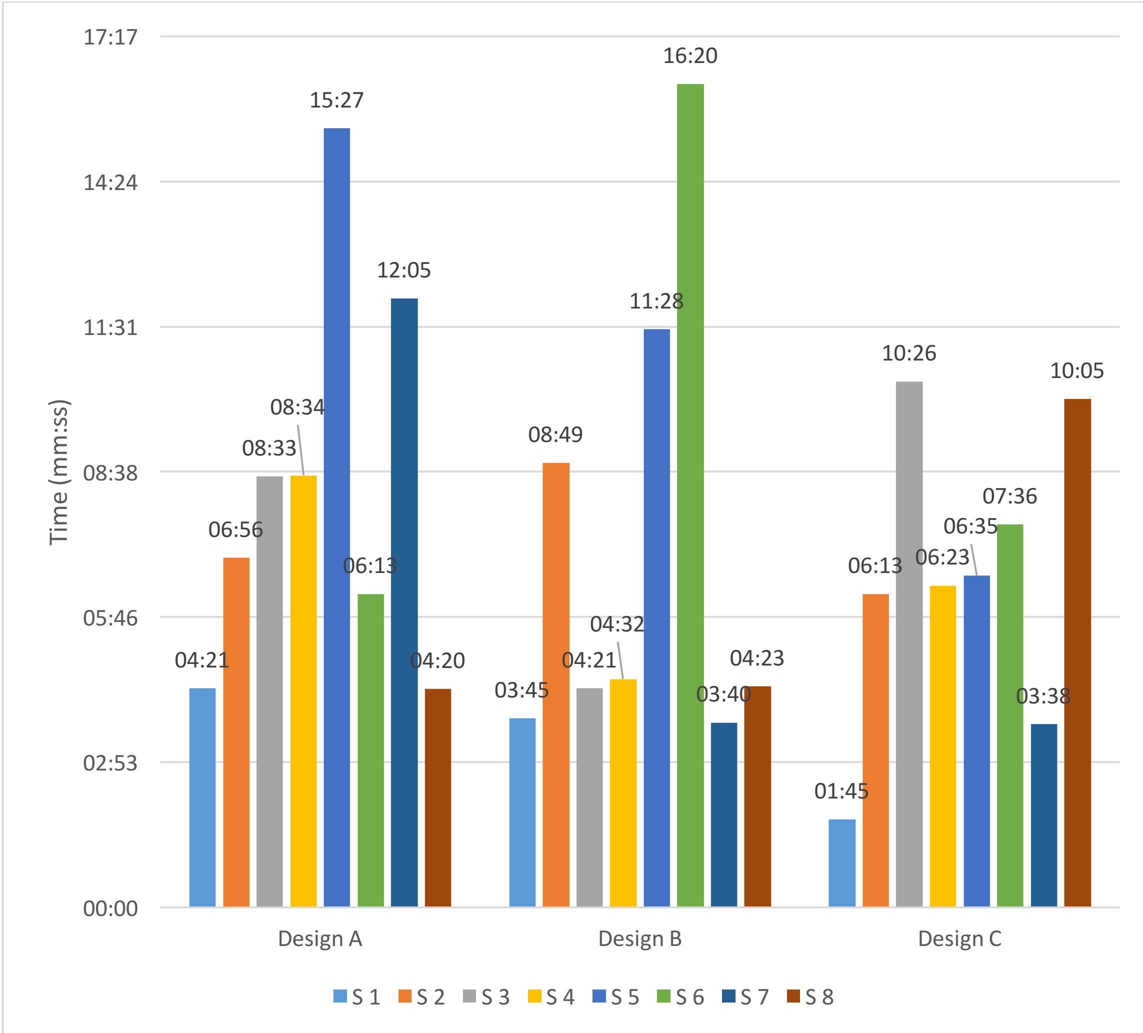


Figure 34: Time (mm:ss) to perform Task 1

Finding from Task 2: improving the constructability of Design A

In Task 2, we asked the participants to tell us how they would improve the constructability of Design A. We categorized the results into correct and incorrect suggestions, as shown below.

Correct Suggestions:

- Resolving conflicts and misalignment within the design (most of the participants)
- Simplifying exterior walls and using prefabricated elements (only one participant)

- Using precast walls instead of brick walls and steel structural frames instead of concrete structural frames (only one participant)
- Adding more detail in the design of exterior walls, interior walls, and roofs (most of participants)

Incorrect Suggestions:

- Adding more details about the furniture and casework (a few participants)
- Adding carpet to the rooms and libraries (a few participants)
- Replacing concrete slabs with post-tensioned slabs (one participant), which this study indicates are less constructible than concrete slabs

Although some participants proposed efficient methods to increase the constructability of designs, most of the designers focused only on the architectural components and their relevant specifications, such as furniture and casework.

Results of the Experimental Study

This section discusses the experiment hypotheses based on data captured during conducting Task 1, Task 2, and Task 3.

<u>Result of the First Hypothesis</u>

The goal of the first hypothesis was to find out if using the BCAEM would help designers evaluate the constructability of designs in less time. We compared the time each participant spent assessing the constructability of the designs manually (Task 1) and with the time required while using the BCAEM (Task 3), as presented in Figure 35, Figure 36, and Figure 37. On average, using the BECAM took a fraction (8%) of the time that participants needed to manually assess the designs. It should be noted that the time involved in using the BECAM, presented in the following figures, is the time that the users interacted with the prototype, selected exchange models, clicked on the assessment button, and read and analyzed the report. Given the results of the time comparison, we can conclude that using the BECAM can help designers assess the construability of buildings in less time.

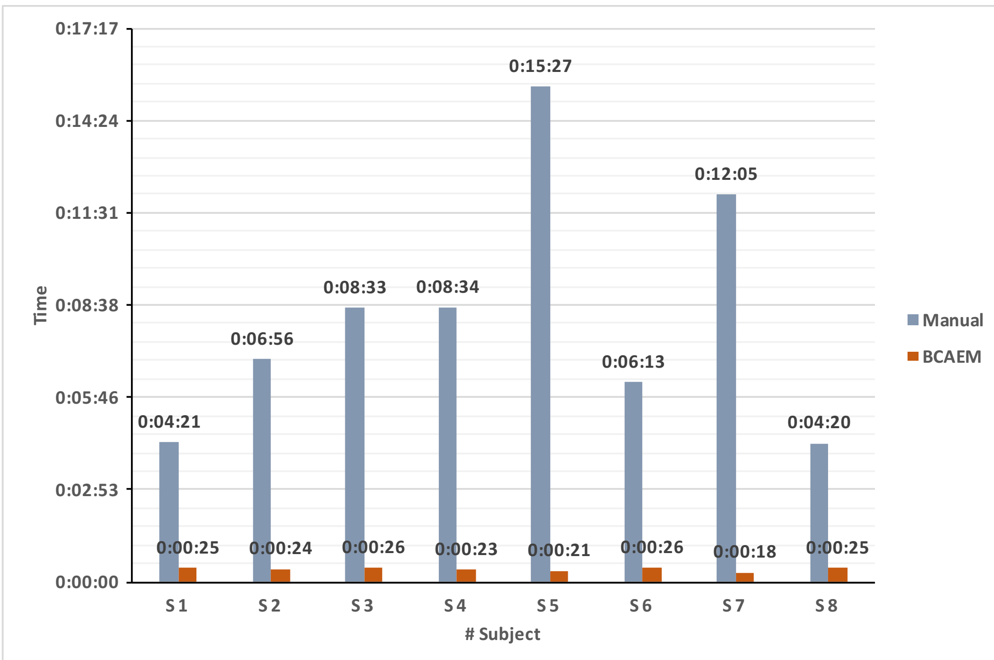


Figure 35: Time to explore the constructability of Design A

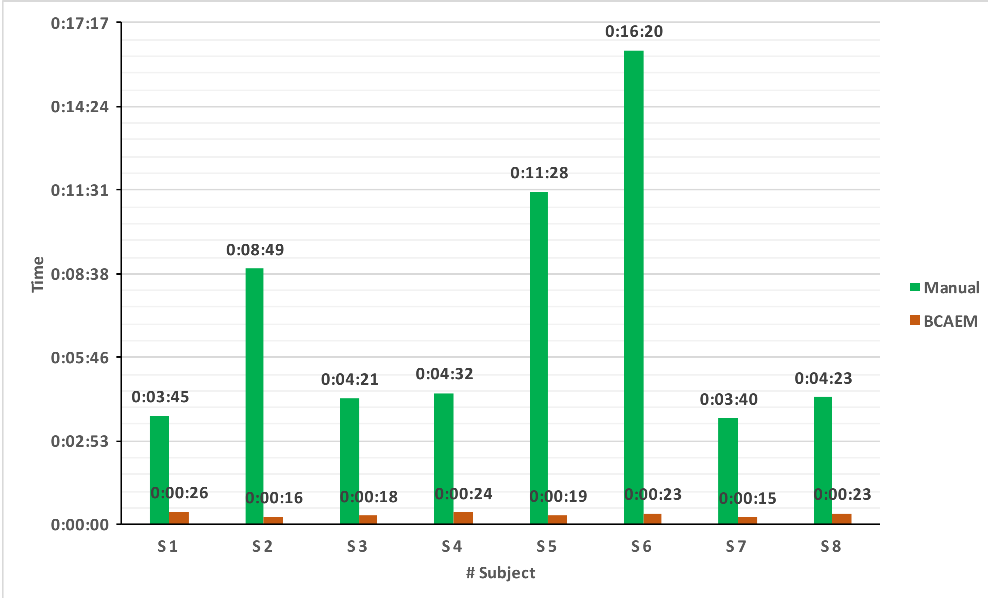


Figure 36: Time to explore the constructability of Design B

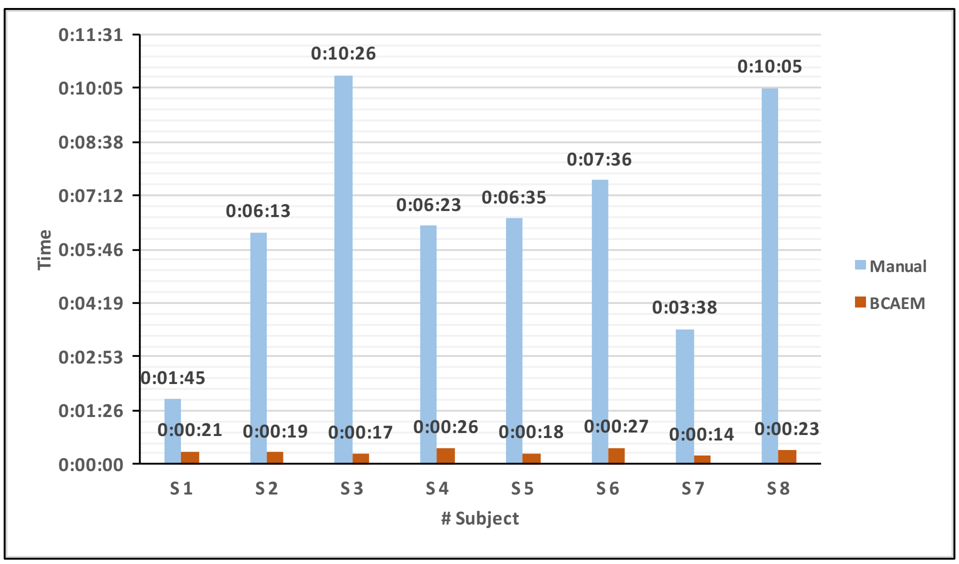


Figure 37: Time to explore the constructability of Design C

Results of the Second Hypothesis

The goal of the second hypothesis was to determine if using the BCAEM would help designers with a more accurate assessment of design constructability. We compared the constructability scores of the designs manually (Task 1) with the scores using the BCAEM (Task 3), presented in Figure 38, Figure 39, and Figure 40. This difference in results demonstrates that while designers think their designs are constructible, contractors may not agree with them. One of the participants also mentioned that in reality, the designers in his company usually think their designs are constructible, but contractors usually ask them to change the designs and make them easier to build. For instance, even though Design A was a semi-complete design, the participants failed to take into account the completeness of the models in rating the constructability of the design. Similarly, Design B was incomplete, but most of the participants rated its constructability over 60 despite the lack of required details. Unlike Design B, Design C was a complete design, but it was comprised of a steel structural frame, cast in-situ concrete slabs, and masonry walls. However, most of the participants did not consider the nature of the construction systems when rating the constructability of the design. Instead, they primarily reviewed furniture, caseworks, and exterior wall systems to produce their ratings.

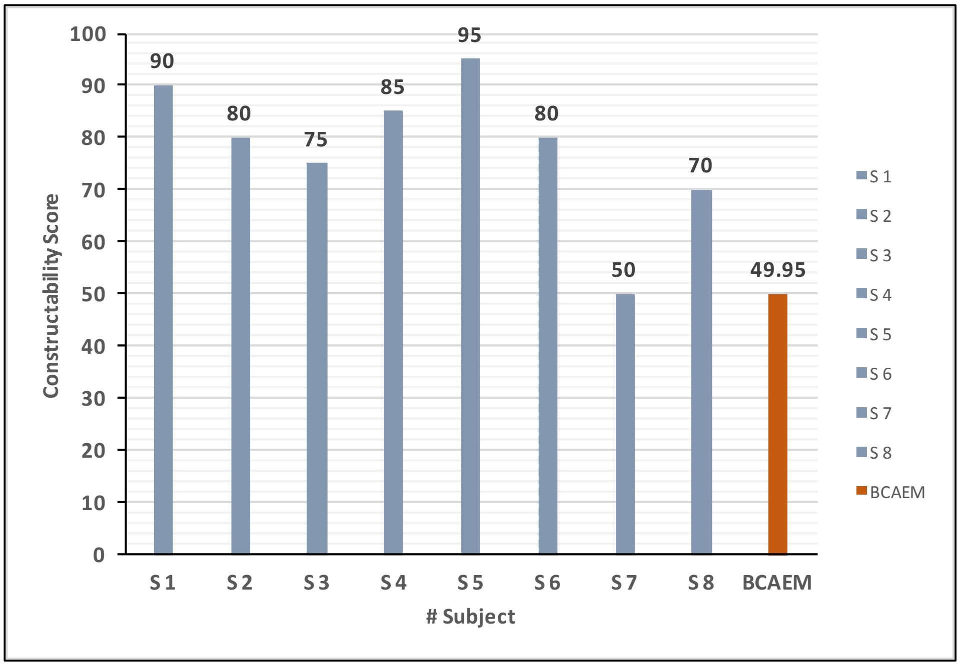


Figure 38: The constructability scores of Design A

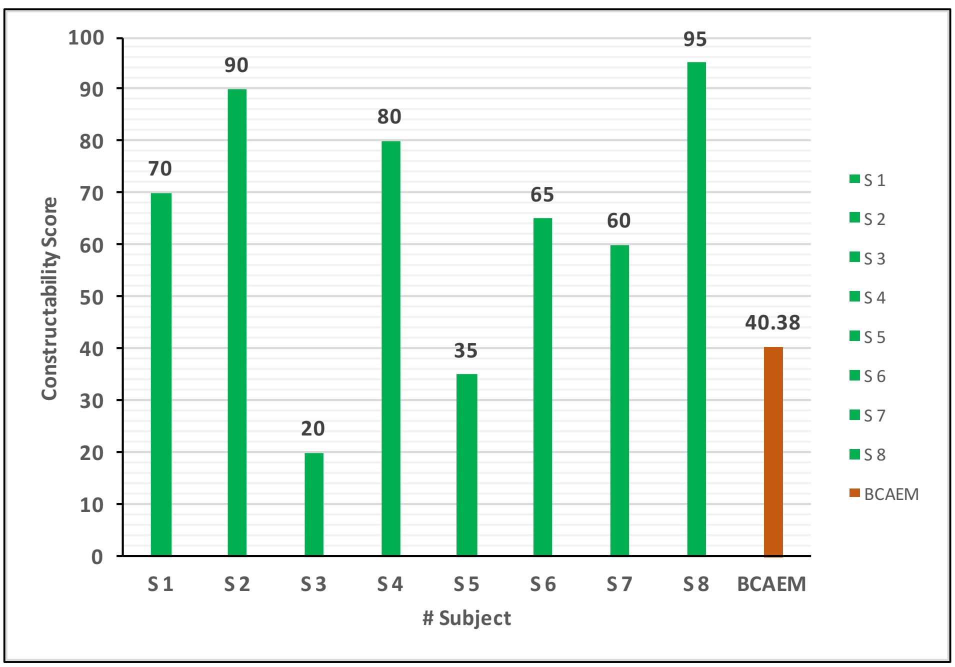


Figure 39: The constructability scores of Design B

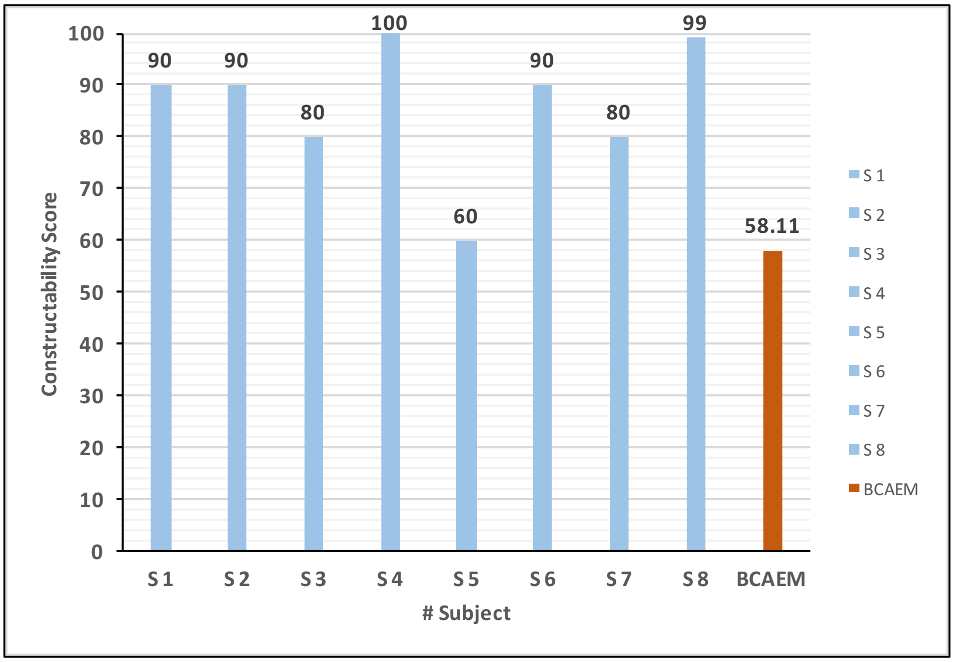


Figure 40: The constructability scores of Design C

We also computed the error in the participants' assessments in connection with our second hypothesis. The errors show the difference between the estimated construability scores by participants (manual calculation) and the calculated scores by BCAEM (automated calculation). The comparison between the manual and automated calculation of constructability shows the average error was 75.37% for Design B, followed by 56.41% for Design A, and 48.21% for design C, yielding a total average error of 60% for all three models (Figure 41). The results also state that BECAM can help designers obtain a more accurate assessment of the constructability of designs.

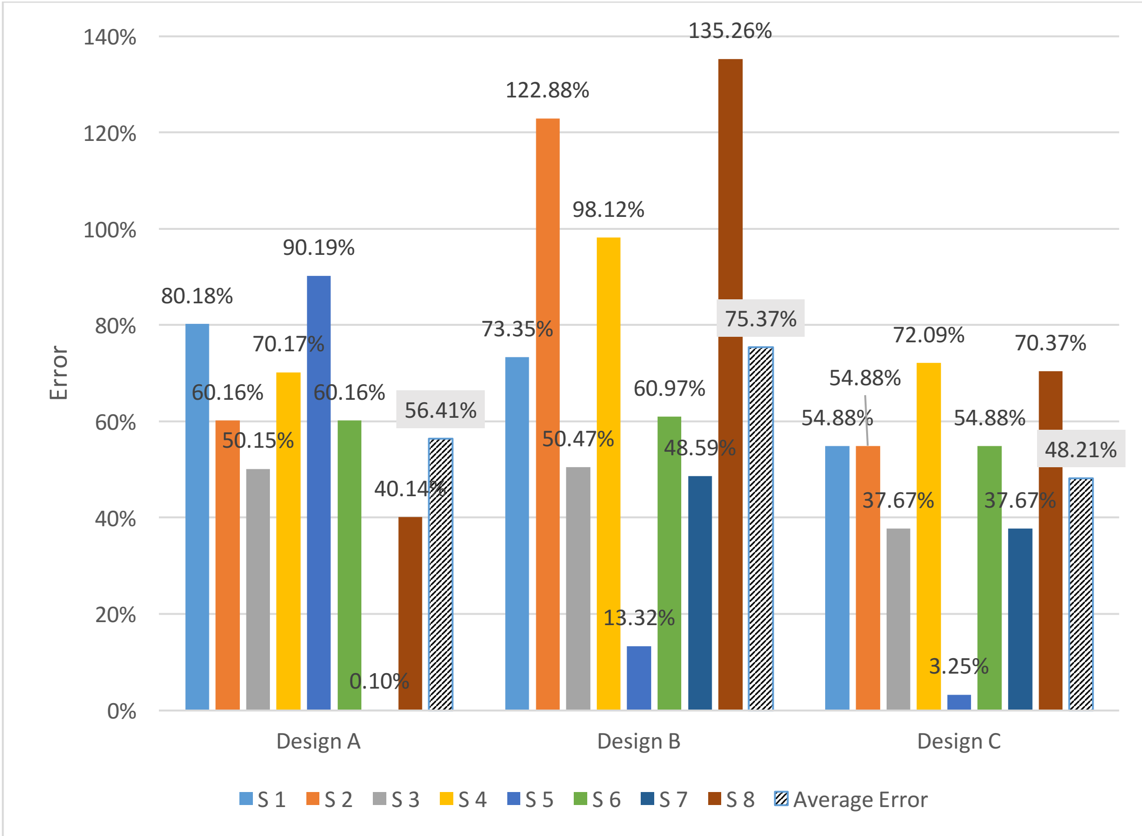


Figure 41: Participants error on constructability assessment

Result of the Third Hypothesis

The goal of the third hypothesis was to find out if using the BCAEM would help designers formalize their method of assessing constructability. Unlike the two other hypotheses, the results of this hypothesis were determined from observation and fact-gathering during the experiments. We observed that constructability has a different meaning for different designers. For instance, some of the designers think constructability can be improved by adding more detail in the design about the furniture and casework or by adding carpet to some of the rooms. This misconception means that, even though some of the designers think about the constructability or try to improve the constructability at the early design stage, their designs still may fail to meet the constructability requirements of contractors. In addition, we observed that some of the designers did not know how to determine the constructability of various building systems. For instance, one of the participants recommended replacing concrete slabs with post-tensioned slabs even though the latter are less constructible from a contractor's point of view.

After using the BECAM, most of the designers mentioned that it provided a consistent way of thinking about constructability. Comments like "interesting … because I was checking furniture for the constructability assessment," "[i]nteresting to see the breakdown of the constructability scores for different elements, and it makes more sense," or the "scores show I should improve the constructability of the structural frame" all support the conclusion that using the BCAEM would help designers with formalizing their methods for assessing constructability.

Post-experiment Questionnaire

At the end of the experiment, the participants filled out the post-experiment questionnaire. As shown in Table 28, the comments showed that the designers felt that they could quickly explore the constructability of more design alternatives (mean response out of 5, Mean= 4.38) and learn more about the constructability of designs (4.13) using the BCAEM. The comments also indicated the BCAEM has value to designers (4.25). For example, the participants mentioned that it could help them understand the kind of information they need to be pulling from the models for their constructability assessment. In addition, they somewhat agreed that they could create more constructible designs using the BCAEM.

Table 28: Descriptive statistics for the post-experiment questionnaire

#Q	Variables	Likert Scale	Mean (SD)
1	I can easily improve the constructability of designs using the constructability assessment model.	1=Strongly Agree to 5=Strongly Agree	4.15 (0.656)
2	I can quickly explore the constructability of design alternatives using the constructability assessment model.		4.38 (0.518)
3	I can learn more about the constructability of designs using the constructability assessment model.		4.13 (0.641)
4	I can create more constructible designs using the constructability assessment model.		3.76 (0.463)
5	I believe the constructability assessment model has values to designer.		4.25 (0.707)

Comments and Recommendations

When the participants conducted Task 3, most of them were surprised by the results from the BCAEM and as the comments quoted above indicate. The participants believed the BCAEM could help them learn more about constructability. For instance, they mentioned, “Good to know that the metal deck system is more constructible than [a] cast-in-situ concrete system,” or “as designers we usually think our designs are constructible, but contractors always return back designs and ask us to change [them],” or the BCAEM can “help [us] know the weaknesses of designs.” They also believed the BCAEM has many potential benefits for designers. For example, they commented that it can“ help with understanding how the major structural elements are defined in the model,” it can “help with pulling out required information out of models based on consistent terms and rules for the constructability assessment,” with the BCAEM “[d]esigners can assess the efficiency of the project beyond cost,” “[i]t is helpful for inexperienced designers,” and it can “ help to find out which parts of designs need more attention in order to make the designs more constructible.”

They also proposed some recommendations for future research such as “[t]ake into account interior doors, interior windows, finishes, or cost estimation,” “include foundation and MEP system," "[a]dd fire protection and MEP system," or "add railing for stairs." In addition, most of the participants were interested in integrating the constructability assessment model with a tool that could provide them instant feedback on the constructability assessment of designs. They also recommended training and educating the construction disciplines, in particular designers, and imposing agency mandates for implementing constructability assessments. A few participants proposed encompassing the trade-off between cost and constructability in exploring design alternatives. Figure 42 and Figure 43 display the percentage of comments and recommendations made by the participants, respectively.

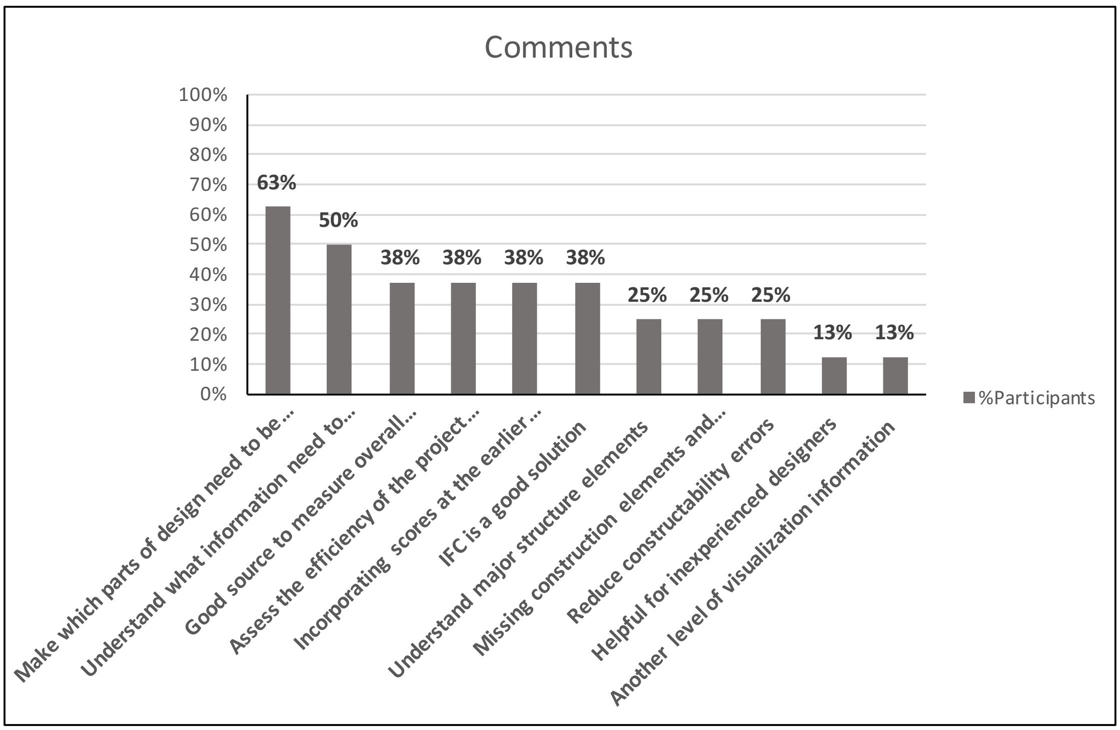


Figure 42: Comments from the participants

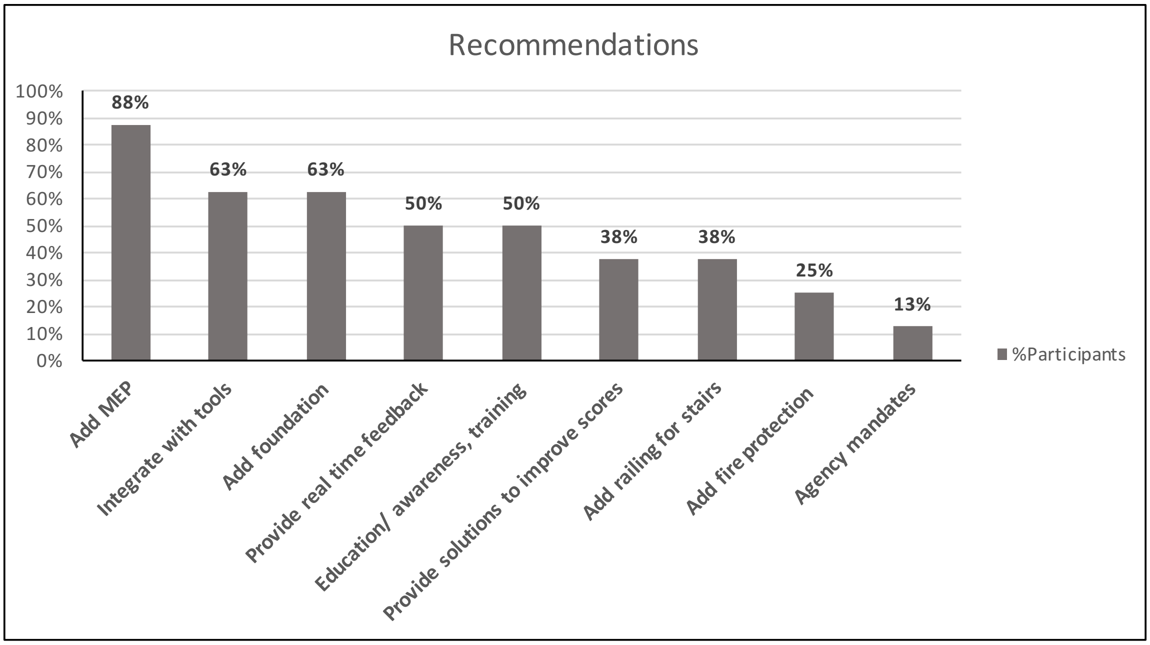


Figure 43: Recommendations from the participants

Summary

The results of this experiment showed that the application of the BCAEM in building construction improves the early-stage constructability assessment of design alternatives. Further, it reduces the time required to conduct the assessment, increases its accuracy, and formalizes the method used. Designers are able to quickly explore the constructability of design alternatives using the BCAEM. It should be noted that software vendors should first implement BCAEM in their BIM platforms so that designers do not need to spend extra time to prepare their models for the constructability assessment. By implementing BCAEM in BIM platforms, designers only need to first select BCAEM and then export the model as an IFC file which is ready for the constructability assessment. The observation during the experiment showed that the BCAEM can assist designers in learning how to increase the constructability of their designs. The designers participating in the experiment quickly learned that space programs, space functionalities, and furniture and caseworks do not really affect how easy a design is to build.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Designers, contractors, owners, and project managers need a model to aid them in increasing the constructability of designs and to expedite their constructability review, because currently, in the early design stage of construction projects, designers often rely on generalized rules to make critical decisions about geometry, construction systems, and materials without evaluating the applicable construction requirements and constraints. Ease of construction, or constructability, is a critical factor that should be examined at the early stage of a construction project when designs are the most amenable to change. Lack of a BIM-based quantitative constructability model for commercial construction projects in the United States motivated us to develop the BCAEM, which reduces the inefficiencies of data overload by providing designers or contractors with standardized information for assessing a design's constructability. Moreover, with the standard format and approach defined in the BCAEM, designers can guarantee consistency in terminology and rules when exchanging data. This chapter presents the main findings of each of this study's objectives, its contributions and limitations, and recommendations for future studies.

Findings from the First Objective

The first objective of this study was to identify and prioritize the essential constructability factors of building designs. We identified seventy-nine constructability attributes and categorized them through surveys and analysis into six constructability factors: 1) building details and design components, 2) resource intelligence and alignment, 3) design standardization, 4) construction site logistics planning and scheduling, 5) innovation, and 6) design review and coordination. We also conducted a survey to determine common construction systems for commercial construction projects in the United States (Table 11).

Findings from the Second Objective

The second objective of this study was to formulate a model for the constructability assessment of building designs. Based on the results of the AHP survey of construction professionals, we formulated the following model for calculating the constructability of commercial building designs. Several construction experts with extensive knowledge and experience contributed to the development of the constructability assessment model, which enables AEC professionals to explore and identify tradeoffs between the constructability of various design alternatives so that they can make informed decisions in selecting the geometry, materials, and various components of building systems at the early stage of the design. It also significantly aids them in gaining an understanding of the implications of construction constraints and requirements on their designs earlier in the design process. The output of the constructability assessment model is a constructability score for the entire building design or a list of constructability scores for each building component, including structural frames, slabs, roofs, internal walls, external walls, and staircases. This constructability assessment model is as follows:

> ***Constructability score of designs*** = *constructability score of structural system + constructability score of slab system + constructability score of internal wall system + constructability score of external wall system + constructability score of roof system + constructability score of staircase system*

OR

Constructability Assessment Model =

$$\{32[\sum(V_s * C_s)] + 12[\sum(A_l * C_l)] + 22[\sum(A_x * C_x)] + 9[\sum(A_n * C_n)] + 18[\sum(A_r * C_r)] + 7[\sum(A_t * C_t)]\},$$

where V_s = Percentage of total volume using a particular structural frame system

A_l = Percentage of total area using a particular slab system

A_x = Percentage of total area using a particular external wall system

A_n = Percentage of total area using a particular internal wall system

A_r = Percentage of total area using a particular roof system

A_t = Percentage of total area using a particular staircase system

C_s = Constructability index for a particular structural frame system (Table 13)

C_l = Constructability index for a particular structural slab system (Table 13)

C_x = Constructability index for a particular external wall system (Table 13)

C_n = Constructability index for a particular internal wall system (Table 13)

C_r = Constructability index for a particular roof system (Table 13)

C_t = Constructability index for a particular staircase system (Table 13)

W_s = Constructability importance of structural frame system (Table 14)

W_l = Constructability importance of slab system (Table 14)

W_x = Constructability importance of external wall system (Table 14)

W_n = Constructability importance of internal wall system (Table 14)

W_r = Constructability importance of roof system (Table 14)

W_t = Constructability importance of staircase system (Table 14).

Findings from the third objective

The third objective of this study was to create a BIM-based EM for a seamless constructability assessment of designs. In a collaborative BIM environment, AEC professionals not only need BIM to visualize and understand building designs but also to exchange building model data between BIM software for various uses in different phases of a project (Jeong et al., 2009). To exchange building model data, AEC professionals generally use the IFC format, which is highly redundant, making it inappropriate for a specific task-related data exchange (Jeong et al., 2009). Thus, they need the MVD approach proposed by NBIMS to identify required data to be exchanged between project disciplines for a specific task or purpose. This study used the same approach to create an EM for the constructability assessment of commercial building designs. The BCAEM has thirty-five concepts, including seven new concepts and twenty-eight adopted or reused concepts from PCI-MVD and BLIS. Such an EM enables designers or domain experts to determine whether a design model has all of the required information and/or building model data for assessing the constructability of the design. Moreover, software vendors can also significantly benefit from the model in evaluating the import and export functions of their IFC translators in terms of the required data for the constructability assessment.

Findings from the Fourth Objective

The fourth objective of this study was to examine the application of the BCAEM. Through our experimental study, we determined that the BCAEM enabled the participants to assess the constructability of the designs faster than with manual estimation. Each participant mentioned different correct or incorrect factors they used in manually assessing the constructability of designs; however, using the BCAEM formalized the method of constructability assessment, so they could identify and understand the appropriate factors to consider in making their assessment. Additionally, the BCAEM helped the designers learn how to increase the constructability of their designs and make them easier to build.

Summary of the Findings

Through conducting this research:

- We developed a quantitative constructability assessment model based on the relative importance of constructability factors and construction systems to help designers in creating more constructible designs.
- We created an exchange model that facilitates faster and accurate BIM-based constructability assessment of building designs.

- We formalized and quantified a method for constructability assessment of designs so that designers can have the same understanding of construction requirements and constraints as the contractors.

Contributions of the Research

Currently, designers lack specified information to aid them in conducting constructability assessments, leaving them to sort through large amounts of information using the limited computing power of BIM platforms, while relying on generalized principles and knowledge gained through past experience. This research determined and documented the information items that designers need for accurately and efficiently analyzing and assessing the constructability of building designs. Figure 44 illustrates the framework used to implement an automated constructability assessment in BIM. The main contribution of this research to practice is to help designers:

- Improve the early-stage constructability assessment of design alternatives;
- Increase the accuracy of the constructability assessment; and
- Reduce the time needed to review the constructability of designs.

In addition, the main contribution of this research to the existing body of knowledge are:

- To improve designers' understanding on how to increase the constructability of designs;
- To have a better understanding of factors affecting constructability;
- To prioritize construction systems based on their constructability scores;
- To determine required and optional values for the attributes of entities (e.g., name and object type) in the exchange model; and
- To identify the to-be exchanged data for the constructability assessment exchange model.

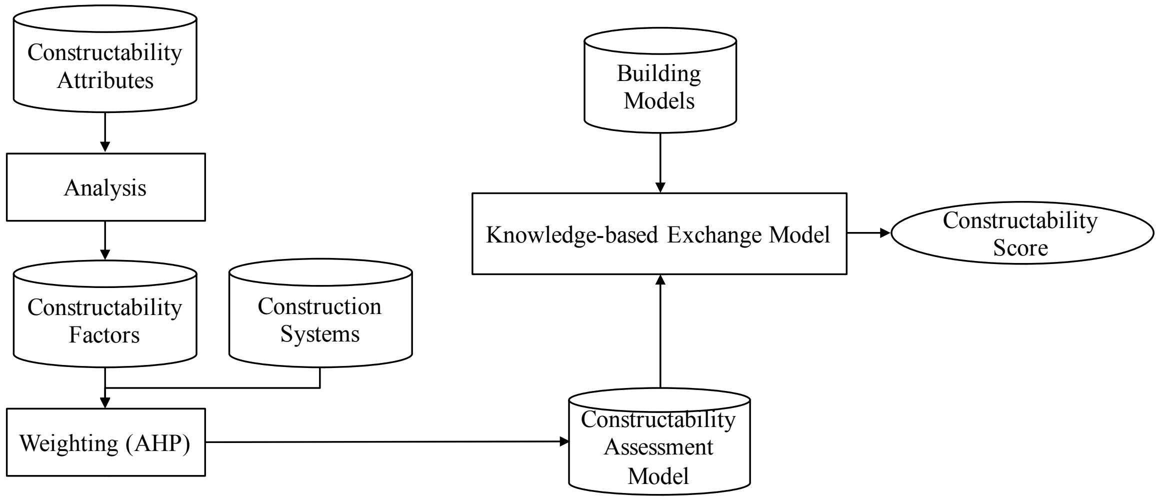


Figure 44: A framework of the application of BCAEM

Limitations of the Research

This study was limited in several ways. First, the constructability model introduced in this study was limited to commercial building projects. Second, the constructability assessment models are not the same in different countries due to regional differences among building codes, standards, construction methods, available resources and labor, working conditions, and culture. The constructability assessment model in this study was based on building codes and construction operations in the United States, so its results may not be applicable to other countries and regions. Further, the model was limited to rational and orthogonal buildings and thus was unable to take into account the impacts of complex forms or geometry on the constructability of designs. The model also was limited to structural frames, slabs, roofs, interior walls, exterior walls, and staircases and did not consider foundation systems and electrical and mechanical components in assessing the constructability of designs. In addition, the model was not applicable for measuring the constructability of detailed components, such as bolts, welds, and discrete accessories. Thus, if designers add more level of details in terms of connections, assemblies, rebar, and discrete accessories in designs, the results of the constructability assessment will not change. Finally, the constructability assessment model developed in this study does not recognize the cost of construction. The constructability score can be a factor in comparing different design alternatives, but a higher constructability score does not necessarily mean lower costs. Therefore, designers and contractors are only able to compare different design alternatives based on their constructability scores and not the comparative costs of construction or materials.

Recommendations for Future Research

This study was the first step toward generating a BIM-based constructability assessment for various types of buildings. Software vendors may implement the constructability assessment EM in their IFC translators so that designers can more easily and quickly explore various design alternatives and assess their constructability levels. However, future research could expand on this study in a number of ways, for example, by creating a system that provides real-time feedback to help designers improve constructability. Additional research could also introduce new features enabling designers or contractors to analyze trade-offs between both cost and constructability, which may allow them to examine the interrelationship between these two factors on scores of projects. Further, future research may expand the constructability assessment model by including other building components, such as foundations, doors, windows, and mechanical, electrical, and plumbing systems, or by adding a greater level of detail allowing the assessment of various types of connections and assemblies. Moreover, the proposed constructability assessment model in this study is based on the results of our survey with a broad range of construction professionals; however, construction companies can tune the model and customize it based on their own requirements and level of expertise.

APPENDIX A

CONSTRUCTABILITY ATTRIBUTES IDENTIFIED FROM THE LITERATURE

No.	Criteria	Reference
1	Enabling efficient site layout and storage	(Nourbakhsh et al., 2012), (Ruby, 2008)
2	Transportation road capacity	(O'Connor et al., 1987)
3	Site conditions	(Tauriainen et al., 2012), (Ruby, 2008), (O'Connor et al., 1987)
4	Access lanes to construction site	(O'Connor et al., 1987)
5	Allowing sufficient working space for labor, materials and machinery on site	(Windapo and Ogunsanmi, 2014), (Ruby, 2008)
6	Traditional external scaffold (e.g., independent or putlog)	(Windapo and Ogunsanmi, 2014)
7	Self-climbing perimeter scaffold	(Windapo and Ogunsanmi, 2014)
8	Crane-lifted perimeter scaffold/fly cage	(Windapo and Ogunsanmi, 2014)
9	Allowing fewer wet trades on site	(Windapo and Ogunsanmi, 2014)
10	Causing less environmental nuisance to surroundings	(Windapo and Ogunsanmi, 2014)
11	Number of floors	(Tauriainen et al., 2014)
12	Maximizing preassembly work	(Fischer and Tatum, 1997)
13	Minimizing scaffolding needs	(O'Connor et al., 1987)
14	Maximizing vendor shop fabrication	(O'Connor et al., 1987), (Ruby, 2008)
15	Minimizing onsite works	(Lam et al., 2007)
16	Minimizing temporary structural supports	(Tauriainen et al., 2014), (Sulankivi et al., 2014), (Navon et al., 2000)
17	Minimizing underground work	(Nourbakhsh et al., 2012),
18	Use of spray painting	(Windapo and Ogunsanmi, 2014)
19	Innovative/efficient construction methods	(Nourbakhsh et al., 2012), (Wong, 2007)
20	Stability of the structural frame during erection	(Tauriainen et al., 2012), Ruby, 2008)
21	Scheduling and ordering element assemblies	(Tauriainen et al., 2014), (Sulankivi et al., 2014)
22	Enabling simplification of construction details	(Kuo and Wium, 2014)
23	Construction costs	(Tauriainen et al., 2012)
24	Simple installation	(Nourbakhsh et al., 2012)
25	Standardized member length	(Tauriainen et al., 2014), (Kuo and Wium, 2014), (Wong, 2007)
26	Thickness of wall	(Jarkas, 2012),
27	Wall curvature intensity	(Jarkas, 2012)
28	Variability of element sizes in floors (i.e., repetition criteria)	(Jarkas, 2012)

No.	Criteria	Reference
29	Number of beams used to support floor areas	(Jarkas, 2015)
30	Number of individual slab panels formed within the floor due to beam-framing plan	(Jarkas, 2015)
31	Average slab panel area in floors	(Jarkas, 2015)
32	Round columns	(Fischer and Tatum, 1997)
33	Curved beams	(Jarkas, 2015)
34	Size (i.e., length, width, and height) of components	(Tauriainen et al., 2014),
35	Area and number of holes in building elements	(Tauriainen et al., 2014)
36	Bolted structural connections	(O'Connor et al., 1987)
37	Number of connections	(Ruby, 2008)
38	Field-welded connections	(Ruby, 2008),
39	Element angle connectivity	(Horn, 2015)
40	Rebar diameter	(Jarkas, 2012)
41	Quantity of reinforcement	(Tauriainen et al., 2014), (Navon et al., 2000), (Fischer, 1991b), (Jarkas, 2012)
42	Type of reinforcement	(Navon et al., 2000), (Fischer, 1991b)
43	Distance between adjacent bars	(Navon et al., 2000), (Fischer, 1991b)
44	Weather consideration (e.g., adjusting timing to avoid carrying out structural work, external finishes, etc., during rainy/typhoon season)	(O'Connor et al., 1987)
45	Traditional timber formwork	(Windapo and Ogunsanmi, 2014)
46	Metal formwork	(Windapo and Ogunsanmi, 2014)
47	No formwork (i.e., stay-in-place precast concrete form system)	(Windapo and Ogunsanmi, 2014)
48	Optimizing use of materials and substances	(Sulankivi et al., 2014)
49	Considering fall protection in designs	(Sulankivi et al., 2014)
50	Allowing safe sequence of trades (e.g., heavy M&E machinery hoisted into position before building is fully enclosed)	(Kuo and Wium, 2014), Windapo and Ogunsanmi, 2014), (Ruby, 2008), (Lam et al., 2007),
51	Ensuring sizes and weights of materials and components safe for workers to handle using commonly available machinery	(Lam et al., 2006), (Tauriainen et al., 2014)
52	Resource analysis and scheduling (e.g., time, cost, and quality)	(Windapo and Ogunsanmi, 2014), (Kuo and Wium, 2014)
53	Implementing measures to improve productivity and performance	(Windapo and Ogunsanmi, 2014)
54	Suggesting non-obligatory construction methods for contractor to consider	(Wong, 2007)
55	Use of cranes/lifting equipment	(Windapo and Ogunsanmi, 2014), (Fischer, 1991b)
56	Use of ceiling inserts/cast-in brackets to support M&E fittings	(Windapo and Ogunsanmi, 2014)
57	Strut free basement construction	(Windapo and Ogunsanmi, 2014)
58	Coordinating drawings and specifications	(Windapo and Ogunsanmi, 2014)

No.	Criteria	Reference
59	Flexible design	(Wong, 2007)
60	Clear and complete design information	(Nourbakhsh et al., 2012)
61	Specifying tolerances for as many items as possible	(Nourbakhsh et al., 2012)
62	Coordinating tolerance specifications for interfacing items (e.g., window frame connected to window opening)	(Wong, 2007)
63	Designing to aid visualization of finished work	(Wong, 2007), (Windapo and Ogunsanmi, 2014)
64	Using blow-up details to examine possible clashes in the design (e.g., building services clashing with reinforcements)	(Windapo and Ogunsanmi, 2014)
65	Designing for optimum use of machinery and equipment	(Wong, 2007)
66	Designing for locally available materials/fittings/products/sub-assemblies	(Wong, 2007)
67	Specifying strong materials/components or providing directions for protecting fragile items	(Wong, 2007)
68	Allowing use of a broad range of materials to fulfill required performance	(Wong, 2007)
69	Materials usage optimization	(Sulankivi et al., 2014), (Tauriainen et al., 2012)
70	Use of machinery and equipment available locally	(Wong, 2007)
71	Economical use of labor and machinery (e.g. Balancing between labor and machinery use to reduce overall cost)	(Kuo and Wium, 2014), (Windapo and Ogunsanmi, 2014)
72	Optimizing the mix of offsite work (e.g., Prefabrication, pre-casting and pre-assembly) and onsite work (e.g., Final leveling and fixing)	(O'Connor et al., 1987),
73	Uncomplicated geometry, layout, and shape for floors and buildings	(Wong, 2007)
74	Allowing modular layout of components	(Wong, 2007)
75	Allowing easy connection between components	(Wong, 2007), (Windapo and Ogunsanmi, 2014)
76	Allowing for early removal of temporary support to leave clear working space	(Wong, 2007)
77	Standardization maximization	(Kuo and Wium, 2014)
78	Labor/skills usage optimization	(Jarkas, 2012), (Nourbakhsh et al., 2012)
79	Visualization tools implementation	(Windapo and Ogunsanmi, 2014), (Wong, 2007)

APPENDIX B

PAPER FORMAT OF THE ONLINE SURVEY

Survey: Constructability Attributes in the Design Stage

Date: ___/___/20_

Subject Number: ______

Dear Respondents,

The objective of this questionnaire is to outline the common constructability factors of building designs, targeting general contractors, designers, subcontractors, suppliers of construction materials and equipment or other professionals working in the area of commercial building designs and construction in the United States.

I greatly appreciate if you can please help me out with filling out this questionnaire survey. If you have any questions, you may contact me at samanehzatgatechdotedu

Thank you,
School of Building Construction,
Georgia Institute of Technology,
Atlanta GA 30332

---Demographic Questions---

1. Which state are you from? ____________________________

2. What is your level of degree?
   □High school diploma
   □Bachelor
   □Masters
   □PhD

3. What is the type of your organization?
   □Contractor
   □Consultant
   □Owner
   □Other: ____

4. What is the job title of your current position?
____

5. How many years of experience do you have in your current job?
   □Less than 1year
   □Between 1 and 5 years
   □Between 6 and 10 years
   □More than 10 years

6. How many years of experience do you have in construction?
   □Less than 1year
   □Between 1 and 5 years
   □Between 6 and 10 years
   □More than 10 years

7. What is the size of your company?
   □Small (less than 100 employees)
   □Small-medium (100-999 employees)
   □Medium (1,000-9,999 employees)
   □Large (more than 10,000 employees)

Constructability Attributes of Building Designs

The Construction Industry Institute (CII) defined "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objectives" as constructability.
Please rate how important the following constructability attributes are on enhancing the ease of construction.
Example: How important is "Efficient Construction Site Layout" to improve the constructability of building designs?

	Don't Know	Not Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Enabling efficient site layout and storage	☐	☐	☐	☐	☐	☐
Transportation road capacity	☐	☐	☐	☐	☐	☐
Site conditions	☐	☐	☐	☐	☐	☐
Access lanes to construction site	☐	☐	☐	☐	☐	☐
Allowing sufficient working space for labor, materials and machinery on site	☐	☐	☐	☐	☐	☐
Traditional external scaffold (e.g., independent or putlog)	☐	☐	☐	☐	☐	☐
Self-climbing perimeter scaffold	☐	☐	☐	☐	☐	☐
Crane-lifted perimeter scaffold/fly cage	☐	☐	☐	☐	☐	☐
Allowing fewer wet trades on site	☐	☐	☐	☐	☐	☐
Please ignore this question	☐	☐	☐	☐	☐	☐
Causing less environmental nuisance to surroundings	☐	☐	☐	☐	☐	☐
Number of floors	☐	☐	☐	☐	☐	☐
Maximizing preassembly work	☐	☐	☐	☐	☐	☐
Minimizing scaffolding needs	☐	☐	☐	☐	☐	☐
Maximizing vendor shop fabrication	☐	☐	☐	☐	☐	☐
Minimizing onsite works	☐	☐	☐	☐	☐	☐
Minimizing temporary structural supports	☐	☐	☐	☐	☐	☐
Minimizing underground work	☐	☐	☐	☐	☐	☐
Use of spray painting	☐	☐	☐	☐	☐	☐
Innovative/efficient construction methods	☐	☐	☐	☐	☐	☐

	Don’t Know	Not Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Stability of the structural frame during erection	▯	▯	▯	▯	▯	▯
Scheduling and ordering element assemblies	▯	▯	▯	▯	▯	▯
Enabling simplification of construction details	▯	▯	▯	▯	▯	▯
Construction costs	▯	▯	▯	▯	▯	▯
Simple installation	▯	▯	▯	▯	▯	▯
Standardized member length	▯	▯	▯	▯	▯	▯
Please leave this question unanswered	▯	▯	▯	▯	▯	▯
Thickness of wall	▯	▯	▯	▯	▯	▯
Wall curvature intensity	▯	▯	▯	▯	▯	▯
Variability of element sizes in floors (i.e., repetition criteria)	▯	▯	▯	▯	▯	▯
Number of beams used to support floor areas	▯	▯	▯	▯	▯	▯
Number of individual slab panels formed within the floor due to beam-framing plan	▯	▯	▯	▯	▯	▯
Average slab panel area in floors	▯	▯	▯	▯	▯	▯
Round columns	▯	▯	▯	▯	▯	▯
Curved beams	▯	▯	▯	▯	▯	▯
Please skip this question	▯	▯	▯	▯	▯	▯
Size (i.e., length, width, and height) of components	▯	▯	▯	▯	▯	▯
Area and number of holes in building elements	▯	▯	▯	▯	▯	▯
Bolted structural connections	▯	▯	▯	▯	▯	▯
Number of connections	▯	▯	▯	▯	▯	▯
Field-welded connections	▯	▯	▯	▯	▯	▯
Element angle connectivity	▯	▯	▯	▯	▯	▯
Rebar diameter	▯	▯	▯	▯	▯	▯
Quantity of reinforcement	▯	▯	▯	▯	▯	▯
Type of reinforcement	▯	▯	▯	▯	▯	▯
Distance between adjacent bars	▯	▯	▯	▯	▯	▯

	Don’t Know	Not Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Weather consideration (e.g., adjusting timing to avoid carrying out structural work, external finishes, etc., during rainy/typhoon season)	☐	☐	☐	☐	☐	☐
Traditional timber formwork	☐	☐	☐	☐	☐	☐
Metal formwork	☐	☐	☐	☐	☐	☐
No formwork (i.e., stay-in-place precast concrete form system)	☐	☐	☐	☐	☐	☐
Optimizing use of materials and substances	☐	☐	☐	☐	☐	☐
Considering fall protection in designs	☐	☐	☐	☐	☐	☐
Please don’t answer this question	☐	☐	☐	☐	☐	☐
Allowing safe sequence of trades (e.g., heavy M&E machinery hoisted into position before building is fully enclosed)	☐	☐	☐	☐	☐	☐
Ensuring sizes and weights of materials and components safe for workers to handle using commonly available machinery	☐	☐	☐	☐	☐	☐
Resource analysis and scheduling (e.g., time, cost, and quality)	☐	☐	☐	☐	☐	☐
Implementing measures to improve productivity and performance	☐	☐	☐	☐	☐	☐
Suggesting non-obligatory construction methods for contractor to consider	☐	☐	☐	☐	☐	☐
Use of cranes/lifting equipment	☐	☐	☐	☐	☐	☐
Please ignore this question	☐	☐	☐	☐	☐	☐
Use of ceiling inserts/cast-in brackets to support M&E fittings	☐	☐	☐	☐	☐	☐
Strut free basement construction	☐	☐	☐	☐	☐	☐
Coordinating drawings and specifications	☐	☐	☐	☐	☐	☐
Flexible design	☐	☐	☐	☐	☐	☐
Clear and complete design information	☐	☐	☐	☐	☐	☐
Specifying tolerances for as many items as possible	☐	☐	☐	☐	☐	☐
Coordinating tolerance specifications for interfacing items (e.g., window frame connected to window opening)	☐	☐	☐	☐	☐	☐
Designing to aid visualization of finished work	☐	☐	☐	☐	☐	☐

	Don't Know	Not Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Using blow-up details to examine possible clashes in the design (e.g., building services clashing with reinforcements)	☐	☐	☐	☐	☐	☐
Designing for optimum use of machinery and equipment	☐	☐	☐	☐	☐	☐
Designing for locally available materials/fittings/products/sub-assemblies	☐	☐	☐	☐	☐	☐
Please leave this question blank	☐	☐	☐	☐	☐	☐
Specifying strong materials/components or providing directions for protecting fragile items	☐	☐	☐	☐	☐	☐
Allowing use of a broad range of materials to fulfill required performance	☐	☐	☐	☐	☐	☐
Materials usage optimization	☐	☐	☐	☐	☐	☐
Use of machinery and equipment available locally	☐	☐	☐	☐	☐	☐
Economical use of labor and machinery (e.g. Balancing between labor and machinery use to reduce overall cost)	☐	☐	☐	☐	☐	☐
Optimizing the mix of offsite work (e.g., Prefabrication, pre-casting and pre-assembly) and onsite work (e.g., Final leveling and fixing)	☐	☐	☐	☐	☐	☐
Uncomplicated geometry, layout, and shape for floors and buildings	☐	☐	☐	☐	☐	☐
Allowing modular layout of components	☐	☐	☐	☐	☐	☐
Please ignore this question	☐	☐	☐	☐	☐	☐
Allowing easy connection between components	☐	☐	☐	☐	☐	☐
Allowing for early removal of temporary support to leave clear working space	☐	☐	☐	☐	☐	☐
Standardization maximization	☐	☐	☐	☐	☐	☐
Labor/skills usage optimization	☐	☐	☐	☐	☐	☐
Visualization tools implementation	☐	☐	☐	☐	☐	☐

What else do you think would affect the constructability of a building design?

Any suggestion or comments?

Thank you very much for your time and collaboration.

APPENDIX C

PAPER FORMAT OF THE AHP SURVEY

Survey: Constructability Assessment of Commercial Buildings in the Design Stage

Date: ___/___/20_

Subject Number: ______

Dear John,

As a part of my PhD research, I need to interview construction contractors, construction managers, and project managers who have work experience in managing commercial construction projects. If you have this experience, I'd like to invite you to participate in a questionnaire survey. Please let me know if you are interested to participate and help. If so, please answer the following questions and send it back to me.

1. What is your current job title?
2. How many years of experience do you have in construction?
3. Have you ever worked as a Construction Contractor, Construction Manager, or Project Manager on any commercial construction project? If so, for how many years?
4. What type of commercial buildings have you worked on?

Look forward to receiving your response. Please let me know if you have any questions or concern.

Thank you,

School of Building Construction,
Georgia Institute of Technology,
Atlanta GA 30332

Section A: Demographic Questions:

1. What is your level of degree?
   □High school diploma
   □Bachelor
   □Masters
   □PhD

2. What is the type of your organization?
   □Contractor
   □Consultant
   □Owner
   □Other: ____

3. What is your current job title?
   □Architect
   □General Contractor
   □Project Manager
   □Structural Engineer
   □Sub-contractor
   □Supplier
   □Other: ------------------------------

4. How many years of experience do you have in construction?
   □Less than 3year
   □Between 3 and 9 years
   □Between 9 and 15 years
   □More than 15 years

5. What is the size of your company?
   □Small (less than 100 employees)
   □Small-medium (100-999 employees)
   □Medium (1,000-9,999 employees)
   □Large (more than 10,000 employees)

6. Have you ever worked as a Construction Contractor, Construction Manager, or Project Manager on any commercial construction project?
   □Yes,
   - for how many years? ---
   - in which states? --

   □No

7. What type of commercial buildings have you worked on?

Example of how to answer Section B:

Question: How important is “**Building elements standardization**” compared to “**Efficient use of resources**” in order to “Improve the Constructability of Commercial Building Designs”?

Answer: the table, **as an example**, shows that the “building elements standardization” factor is absolutely important (9) compared to the “efficient use of resources” factor, Or the “building elements standardization” is strongly important (5) compared to “design standardization and prefabrication” factor.

Building elements standardization	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Efficient use of resources
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Design standardization & prefabrication
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Efficient const. site planning &scheduling
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Innovation
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Design review & coordination

Example of how to answer Section C:

Question: Considering “**Building Elements Standardization**” factor, how constructible “Cast in-situ RC frame” is compared to “In-situ loadbearing wall”?

Answer: the table, **as an example**, shows that the “Cast in-situ RC frame” is equally constructible (1) compared to the “In-situ loadbearing wall” by considering the “building elements standardization” factor, Or “Masonry” is between strongly (5) and very strongly (7) constructible (6) compared to the “Cast in-situ RC frame” by considering the “building elements standardization” factor.

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1	1 2 3 4 5 6 7 8 9	Timber structural frame

Section B: Pairwise Comparison between Constructability Factors

How important is “Building elements standardization” compared to “Efficient use of resources” in order to “Improve the Constructability of Commercial Building Designs”?

Table1. In the Context of “Improve the Constructability of Building Designs”

Building elements standardization	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Efficient use of resources
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design standardization & prefabrication
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Efficient const. site planning &scheduling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Innovation
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design review & coordination
Efficient use of resources	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design standardization & prefabrication
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Efficient const. site planning & scheduling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Innovation
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design review & coordination
Design standardization & prefabrication	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Efficient const. site planning & scheduling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Innovation
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design review & coordination
Efficient const. site planning & scheduling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Innovation
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design review & coordination
Innovation	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Design review & coordination

Note: Pairwise comparison scales

Intensity of Importance	Definition	Definition
1	Equal importance	Two element **equally** important to achieve the goal
3	Moderate importance	One element **moderately** favor over another to achieve the goal
5	Strong importance	One element **strongly** favor over another to achieve the goal
7	Very strong importance	One element **very strongly** favor over another to achieve the goal
9	Absolute importance	One element **absolutely** favor over another to achieve the goal
2,4,6,8	**Intermediate values** between to adjacent judgment	

Section C: Pairwise Comparison between Alternatives

Please consider "**Building Elements Standardization**" for answering the following questions.

Table C-1: Structural Frame

Example: Considering "**Building Elements Standardization**", how constructible "Cast in-situ RC frame" is compared to "In-situ loadbearing wall"?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-2: Slab

Example: Considering "**Building Elements Standardization**", how constructible "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-3: Roof

Example: Considering "**Building Elements Standardization**", how constructible "In-situ concrete roof" is compared to "Precast concrete roof"?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-4: Internal Wall

Example: Considering "**Building Elements Standardization**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-5: External Wall

Example: Considering "**Building Elements Standardization**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-6: Staircase

Example: Considering "**Building Elements Standardization**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Please consider “**Efficient use of resources”** for answering the following questions.

Table C-7: Structural Frame

Example: Considering “**Efficient use of resources**”, how constructible “Cast in-situ RC frame” is compared to “In-situ loadbearing wall”?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-8: Slab

Example: Considering "**Efficient use of resources**", how constructible "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-9: Roof

Example: Considering "**Efficient use of resources**", how constructible "In-situ concrete roof" is compared to "Precast concrete roof"?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-10: Internal Wall

Example: Considering "**Efficient use of resources**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-11: External Wall

Example: Considering "**Efficient use of resources**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-12: Staircase

Example: Considering "**Efficient use of resources**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Please consider "**Design Standardization & Prefabrication"** for answering the following questions.

Table C-13: Structural Frame

Example: Considering "**Design Standardization & Prefabrication**", how constructible "Cast in-situ RC frame" is compared to "In-situ loadbearing wall"?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-14: Slab

Example: Considering "**Design Standardization & Prefabrication**", how constructible "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-15: Roof

Example: Considering "**Efficient use of resources**", how constructible "In-situ concrete roof" is compared to "Precast concrete roof"?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-16: Internal Wall

Example: Considering "**Design Standardization & Prefabrication**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-17: External Wall

Example: Considering "**Design Standardization & Prefabrication**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-18: Staircase

Example: Considering "**Design Standardization & Prefabrication**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Please consider “**Efficient construction site planning & scheduling”** for answering the following questions.

Table C-19: Structural Frame

Example: Considering “**Efficient construction site planning & scheduling**”, how constructible “Cast in-situ RC frame” is compared to “In-situ loadbearing wall”?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-20: Slab

Example: Considering "**Efficient construction site planning & scheduling**", how constructible "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-21: Roof

Example: Considering "**Efficient construction site planning & scheduling**", how constructible "In-situ concrete roof" is compared to "Precast concrete roof"?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-22: Internal Wall

Example: Considering "**Efficient construction site planning & scheduling**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-23: External Wall

Example: Considering "**Efficient construction site planning & scheduling**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-24: Staircase

Example: Considering "**Efficient construction site planning & scheduling**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Please consider "**Innovation**" for answering the following questions.

Table C-25: Structural Frame

Example: Considering "**Innovation**", <u>how constructible</u> "Cast in-situ RC frame" is compared to "In-situ loadbearing wall"?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-26: Slab

Example: Considering "**Innovation**", <u>how constructible</u> "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ

		concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-27: Roof

Example: Considering “**Innovation**”, how constructible “In-situ concrete roof” is compared to “Precast concrete roof”?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-28: Internal Wall

Example: Considering "**Innovation**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-29: External Wall

Example: Considering "**Innovation**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-30: Staircase

Example: Considering "**Innovation**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Please consider "**Design Review & Coordination"** for answering the following questions.

Table C-31: Structural Frame

Example: Considering "**Design Review & Coordination**", how constructible "Cast in-situ RC frame" is compared to "In-situ loadbearing wall"?

Cast in-situ RC frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ loadbearing wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
In-situ loadbearing wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Masonry
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Masonry	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Metal stud frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post-tensioning structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Post-tensioning structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-engineered metal building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-engineered metal building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-tensioning Structure
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Pre-tensioning Structure	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete frame
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Precast concrete frame	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel encased in concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Steel encased in concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Structural steel w/ fire proofing
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame
Structural steel w/ fire proofing	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber structural frame

Table C-32: Slab

Example: Considering "**Design Review & Coordination**", how constructible "Flat slab" is compared to "In-situ RC slab"?

Flat slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ RC slab
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
In-situ RC slab	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Post tensioned concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Post tensioned concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-stressed concrete
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Pre-stressed concrete	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast slab w/ in-situ topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Precast slab w/ in-situ topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel deck w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system
Steel deck w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber frame flooring system

Table C-33: Roof

Example: Considering "**Design Review & Coordination**", how constructible "In-situ concrete roof" is compared to "Precast concrete roof"?

In-situ concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast concrete roof
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Precast concrete roof	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Pre-Engineered Metal Building
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Pre-Engineered Metal Building	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber roof truss
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Prefabricated timber roof truss	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel decking w/ in-situ concrete topping
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel decking w/ in-situ concrete topping	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel truss roof w/ composite decking
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses
Steel truss roof w/ composite decking	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber roof trusses

Table C-34: Internal Wall

Example: Considering "**Design Review & Coordination**", how constructible "Cast in-situ wall w/ applied finishes" is compared to "Concrete block/ brick w/ applied finishes"?

Cast in-situ wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Concrete block/ brick w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Concrete block/ brick w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall (partitions)
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Dry wall (partitions)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight brick
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight brick	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Light weight panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Light weight panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal stud
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Metal stud	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precast wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precision block wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall
Precision block wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Traditional brick and plaster wall

Table C-35: External Wall

Example: Considering "**Design Review & Coordination**", how constructible "Precast concrete wall w/ pre-installed windows and finishes" is compared to "Curtain wall"?

Precast concrete wall w/ pre-installed windows and finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Curtain wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes

	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Curtain wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	In-situ concrete wall
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
In-situ concrete wall	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Precast sandwich panel w/ in-situ filling
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Precast sandwich panel w/ in-situ filling	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Block wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Block wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Brick wall w/ applied finishes
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Brick wall w/ applied finishes	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Metal cladding
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Metal cladding	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Full height glass panel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated timber
Full height glass panel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system
Prefabricated timber	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Dry wall system

Table C-36: Staircase

Example: Considering "**Design Review & Coordination**", how constructible "Cast-in-place" is compared to "Prefabricated"?

Cast-in-place	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Prefabricated
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Prefabricated	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Steel
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber
Steel	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Timber

Any suggestion or comments?

APPENDIX D

CONSTRUCTABILITY EXCHANGE MODEL SPECIFICATIONS

The following table represents the detailed specifications of the constructability exchange model, BCAEM. The definitions of the variables in the table are as follows (Eastman et al., 2009b):

- **Information Group**: It refers to the main classes of objects in building models.
- **Information Items**: It presents items which share the same attributes in each information group.
- **Attribute Set**: It provides a set of properties defining an information group.
- **Attribute**: It refers to properties describing an information group.
- **Rules**:
    - ***Property status***: It identifies whether the properties of each attribute are 'Required' (R) or 'Optional' (O). If a property is 'Required', a model is valid if the property is available in the model. If a property is 'Optional', a model is valid either the property is available in the model or not.
    - ***Geometry function***: It identifies if a geometry is 'Viewable' (V), 'Referenceable' (F), or 'Editable' (E). If a geometry of an object is 'Viewable', users can only see the object without any ability to reference or edit it. If a geometry of an object is 'Referenceable', users can view and use it as reference to create associated geometry. If a geometry of an object is 'Editable', users can edit it.

Information Group	Information Items	Attribute Set	Attributes	Rules	
Project: Participants					**BCAEM**
	Owner, Architect of Record, Engineer of Record, General Contractor, Construction Manager	Identity	Name, Function	Required?	O
		Contact Info	Addresses	Required?	O
			Phones, email, etc.	Required?	O
Project: Site					
	Site	Perimeter	2D Geometry	Required?	O

Information Group	Information Items	Attribute Set	Attributes	Rules	
				Function?	V
		Location	Longitude, Latitude, Orientation	Required?	O
		Topography	Digital terrain model or contours	Required?	O
				Function?	F
		Assembly relations	Contains buildings…	Required?	R
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R
Building(s)					
	Building	Location on site	Position and orientation	Required?	R
				Function?	F
		Grid geometry & control planes	Origin, directions, steps, labels	Required?	R
		Assembly relations	Located on site…	Required?	R
			Contains building systems…	Required?	R
		Association relations	Other buildings on site…	Required?	R
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R
Spaces					
	Building Stories	Geometry	Plan Outline, Heights, Voids, Elevations	Required?	R
				Function?	F
			Net and gross area	Required?	R
			Net and gross volume	Required?	R

Information Group	Information Items	Attribute Set	Attributes	Rules	
		Position	Above, below grade, % open	Required?	R
		Assembly relations	Located in building…	Required?	R
			Contains building systems…	Required?	R
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R
Structure					
	Beams, Columns, Walls, Stairs, Roof	Shape	Geometry	Required?	R
				Function?	F
			Gross/Net Area	Required?	R
			Gross/Net Volume	Required?	R
			Openings/Voids geometry	Required?	R
			Dimensional Tolerance Info	Required?	R
		Layout Geometry	Position and orientation	Required?	R
				Function?	F
		Grid geometry	Origin, directions, steps, reference surface, label	Required?	R
		Type	Construction Type	Required?	R
		Finishes	surface polygon, depth	Required?	O
				Function?	F
			Material Type References	Required?	R
		Supplier	GC/Contractor/Fabricator type/name	Required?	O
		Material	Material type	Required?	R
			Quantity	Required?	R

Information Group	Information Items	Attribute Set	Attributes	Rules	
		Assembly relations	Part of building	Required?	R
			Contains openings…	Required?	R
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R
Openings					
	Doors, Windows, Openings	Position and Geometry	Position, orientation, shape	Required?	R
				Function?	F
			Location constraints	Required?	R
		Specification	Opening type	Required?	R
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R
Finish Material Types					
		Material	Material type	Required?	R
			Surface treatment application details	Required?	R
		Patterns	Geometry	Required?	O
				Function?	F
		Production	Status	Required?	O
			History	Required?	O
			Supplier	Required?	O
			Condition	Required?	O
		Meta Data	Author, Version, Date	Required?	R
			Approval Status, Date	Required?	R

APPENDIX E

BCAEM CONCEPT DEFINITIONS

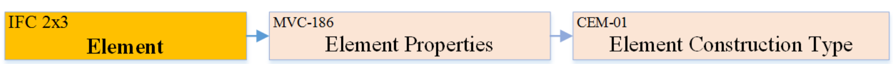
BCAEM consists of 36 concepts, including seven new concepts and 29 reused or adopted concepts from PCI and BLIS Consortium. It also includes about 75 attributes and rules and also eight checking rule types. We created the concepts based on the NBIM standard format. Some of the concepts and their important features are presented here, and the rest of the concepts are available upon request.

IFC Release Specific Concept Description (IFC 2x3)

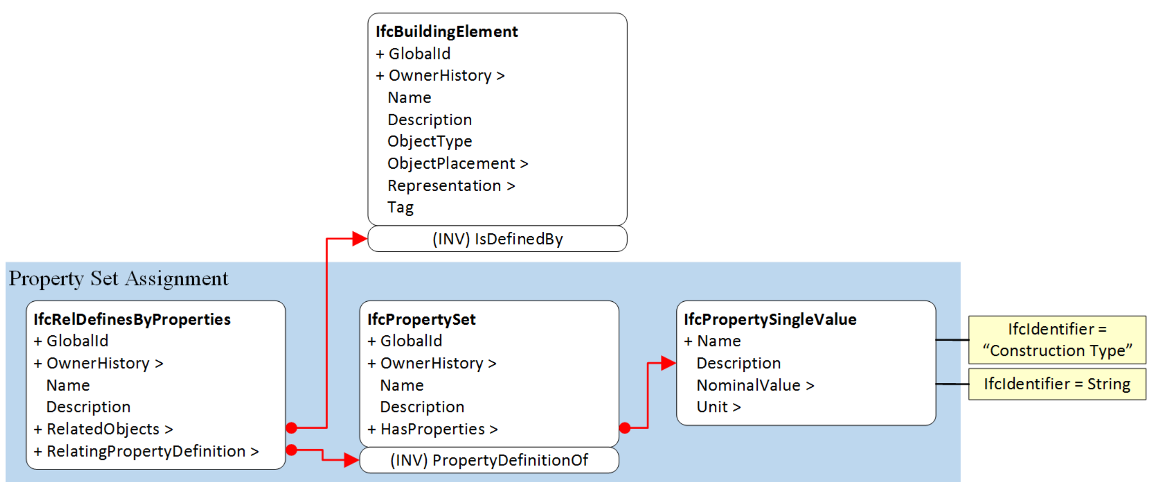
Structural Frame Construction Type

Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Associates construction type with a subtype of structural frame.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project-Georgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcBeam, IfcColumn

IfcRelDefinesByProperties

Attribute	**Implementation agreements**
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	**Implementation agreements**
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

Attribute	**Implementation agreements**
Name	IfcLabel = STRING = “Construction Type”
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

Element	Name
Structural Frame (Beam & Column)	Cast in-situ RC frame
	In-situ loadbearing wall
	Masonry
	Metal stud frame
	Post-tensioning structure
	Pre-engineered metal building
	Pre-tensioning structure
	Precast concrete frame
	Steel encased in concrete (composite structure)
	Structural steel with fire proofing
	Timber structural frame

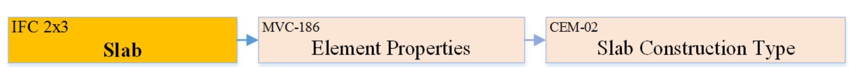
This document uses the official IFC Model View Definition Format version 1.1.0. of the IAI (www.iai-international.org) The content of this document has to be certified by the IAI before becoming part of an official IFC Model View Definition.

IFC Release Specific Concept Description (IFC 2x3)

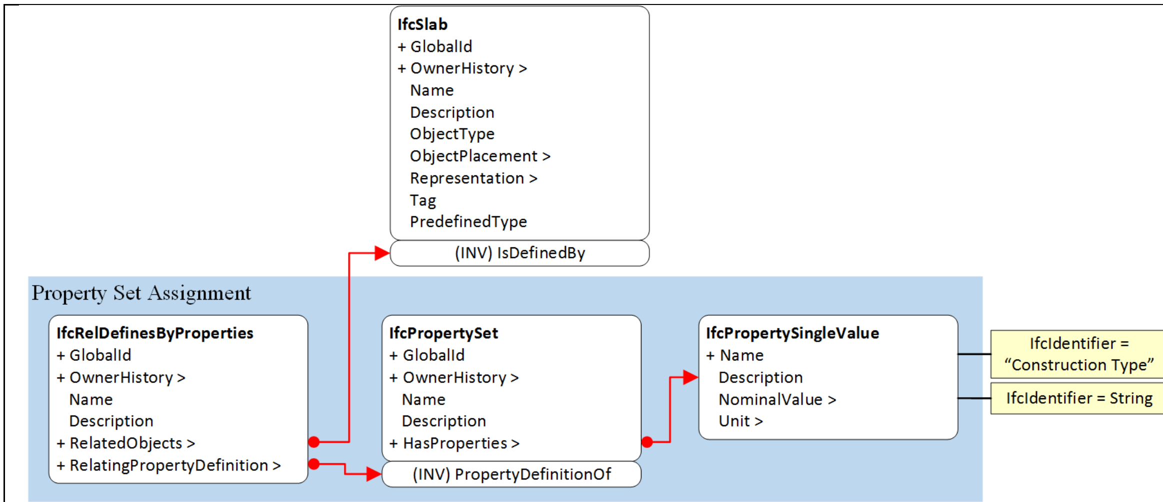
Slab Construction Type

Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Associates construction type of slab or slab Type.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project-Georgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcSlab

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

Attribute	Implementation agreements
Name	Must be IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	Must be a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

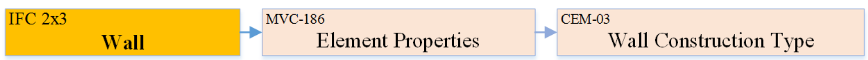
Element	Name
Slab	Flat slab
	In-situ RC slab
	Post tensioned concrete
	Pre-stressed concrete
	Precast slab with in-situ topping
	Steel deck with in-situ concrete topping
	Timber frame flooring system

Example: Part21 file for IfcSlab construction type assignments

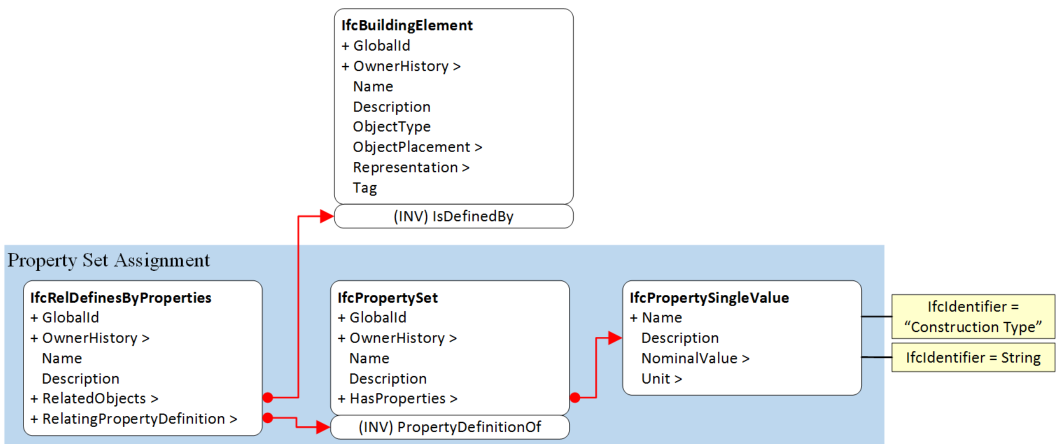
```
…
#4101= IFCLOCALPLACEMENT(#27,#45);
#50= IFCSLAB('1FEI3U000sVZ4pCZanDpCq',#5,'Slab','500X1000','Flat slab
piece',#4101,#49,'TS_4201',.FLOOR.);
#51=
IFCSLABTYPE('3tzijQMNHA8QMweTh8UocH',#5,'500X1000',$,'Slab',$,(#75),$,'FLOOR',.NOTDEFIN
ED.);
#75= IFCREPRESENTATIONMAP(#10,#47);
#100001312=
IFCRELDEFINESBYPROPERTIES('00TIlPtieson0g0aeArkTlH3',#5,$,$,(#50),#100001412);
#100001412=
IFCPROPERTYSET('85PllPtieson0g0aeArkTlH3',#5,'Pset_ElementGeneral',$,(#100001513));
#100001513= IFCPROPERTYSINGLEVALUE('Construction Type', $, IFCIDENTIFIER('Precast slab
with in-situ topping'),$);
```

IFC Release Specific Concept Description (IFC 2.x3) **Wall Construction Type**					
Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Associates construction type of wall or wall Type.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment ProjectGeorgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcWall, IfcWallStandardCase, IfcCurtainWall

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Must be provided: "Internal Wall" or "External Wall"
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

Attribute	Implementation agreements
Name	IfcLabel = STRING = “Construction Type”
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

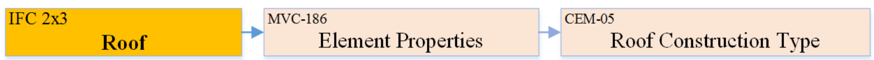
Element	Name	Element	Name
Internal Wall	Cast in-situ wall with applied finishes	External Wall	Precast concrete wall with pre-installed windows and finishes
	Concrete block/brick with applied finishes		Curtain wall
	Dry wall (partitions)		In-situ concrete wall
	Light weight brick		Precast sandwich panel with in-situ filling
	Light weight panel		Block wall with applied finishes
	Metal stud		Brick wall with applied finishes
	Precast wall with applied finishes		Metal cladding
	Precision block wall		Prefabricated timber panel
	Traditional brick and plaster wall		Full height glass panel
			Prefabricated timber
			Dry wall system

IFC Release Specific Concept Description (IFC 2x3)

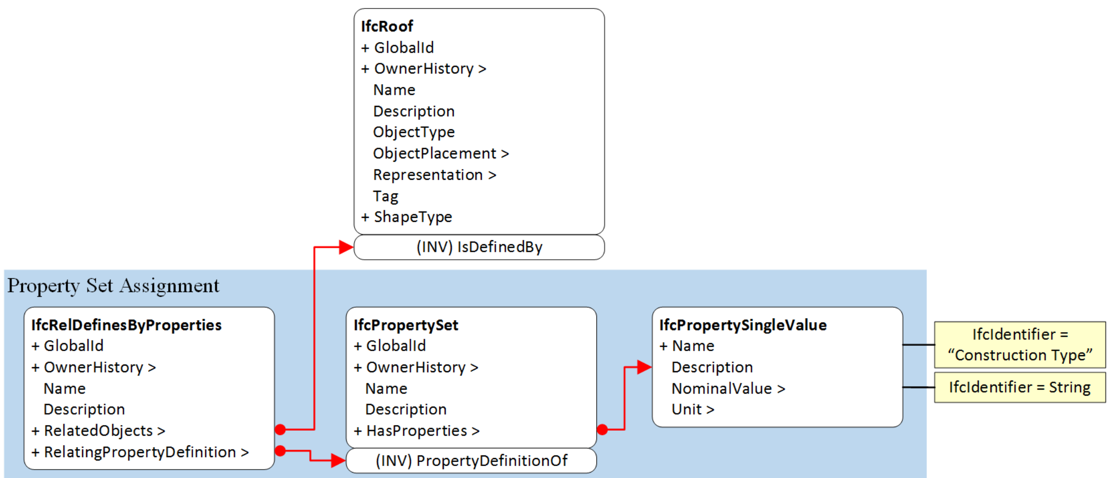
Roof Construction Type

Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Associates construction type of roof or roof Type.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project-Georgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

[IfcRoof]

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

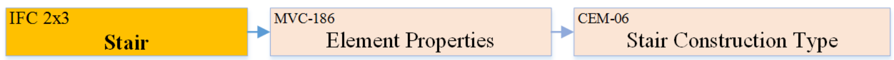
Attribute	Implementation agreements
Name	IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

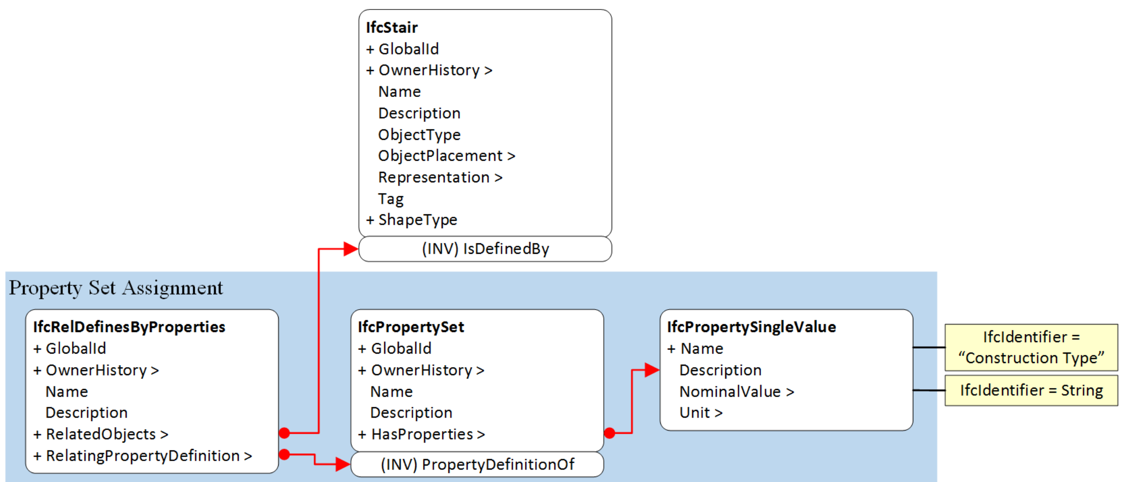
Element	Name
Roof	In-situ concrete roof
	Precast concrete roof
	Pre-engineered metal building
	Prefabricated timber roof truss
	Steel decking
	Steel decking with in-situ concrete topping
	Steel truss roof with composite decking
	Timber roof trusses

IFC Release Specific Concept Description (IFC 2x3)					
Stair Construction Type					
Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Associates construction type of stair or stair Type.				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project-Georgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcStair

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	<Open>
Description	<Open>
RelatedObjects	Must be from the above list.
RelatingPropertyDefinition	A property set which is assigned to elements

IfcPropertySet

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Pset_ElementGeneral
Description	<Open>
HasProperties	Contained set of properties pertinent to construction type from the below table

IfcPropertySingleValue

Attribute	Implementation agreements
Name	IfcLabel = STRING = "Construction Type"
Description	Not used.
NominalValue	This is a STRING that indicated the construction type property.
Unit	Not used for this property

Property Definitions:

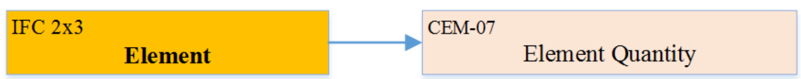
Element	Name
Staircase	Cast-in-place
	Prefabricated
	Steel
	Timber

IFC Release Specific Concept Description (IFC 2x3)

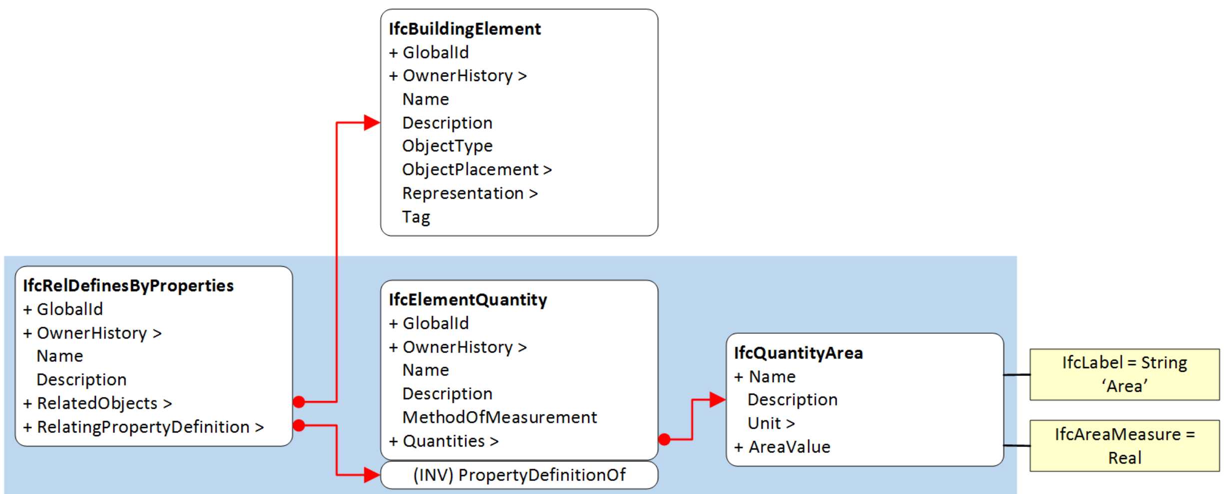
Element Quantities- I

Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Area of elements or a subtype of elements				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment Project-Georgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcRoof, IfcSlab, IfcSlabType, IfcStair, IfcWall, IfcWallType, IfcOpeningElement

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	'Element Quantities'

Description	<Open>
RelatedObjects	Must be a building element from the above list.
RelatingPropertyDefinition	An instance of the an ElementQuantity

IfcElementQuantity

Attribute	**Implementation agreements**
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	‘Element Quantities’
Description	<Open>
MethodOfMeasuremnet	<Open>
Quantities	Contained a set of properties from building elements

IfcQuantityArea

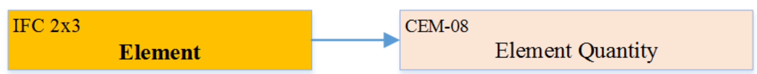
Attribute	**Implementation agreements**
Name	IfcLabel = STRING = “Area”
Description	Total area of elements
Unit	<Open>
VolumeValue	IfcAreaMeasure

IFC Release Specific Concept Description (IFC 2.x3)

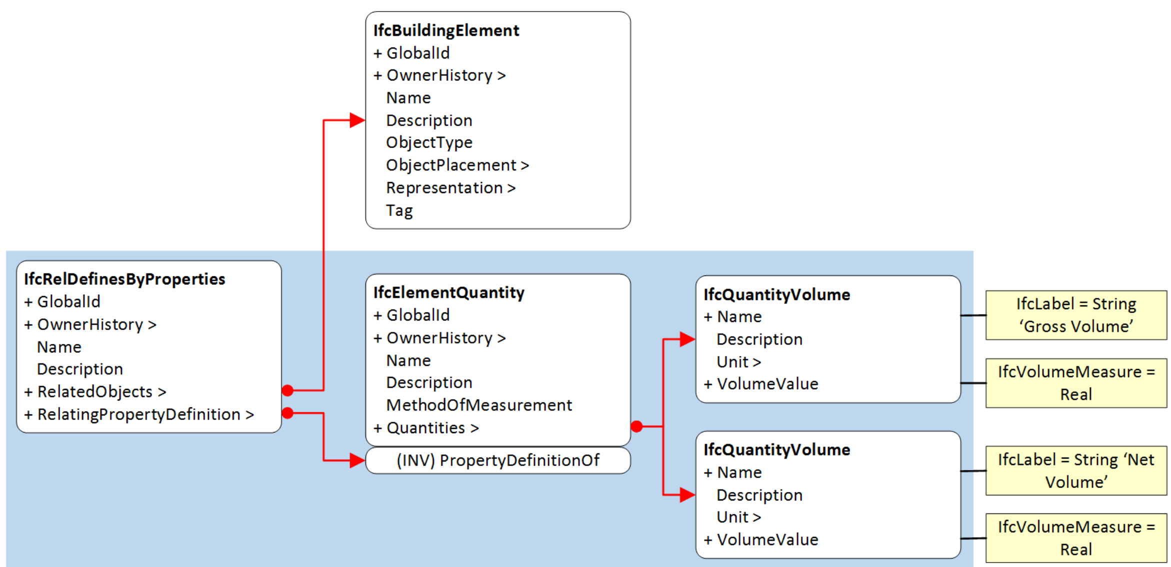
Element Quantities-II

Reference	CEM	**Version**	1.1	**Status**	Draft
Relationships	Net volume or gross volume of structural frame (columns and beams)				
History	Created May, 2016				
Authors	Samaneh Zolfagharian				
Document Owner	Constructability Assessment ProjectGeorgia Tech				

Usage in view definition diagram



Instantiation diagram



Implementation agreements

IfCBuildingElement (ABS) – This must be one of the following:

IfcBeam, IfcBeamType, IfcColumn, IfcColumnType

IfcRelDefinesByProperties

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	'Element Quantities'

Description	<Open>
RelatedObjects	Must be a building element from the above list.
RelatingPropertyDefinition	An instance of the an ElementQuantity

IfcElementQuantity

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	'Element Quantities'
Description	<Open>
MethodOfMeasuremnet	<Open>
Quantities	Contained a set of properties from building elements

IfcQuantityVolume

Attribute	Implementation agreements
Name	IfcLabel = STRING = "Net Volume"
Description	Net volume
Unit	<Open>
VolumeValue	IfcVolumeMeasure

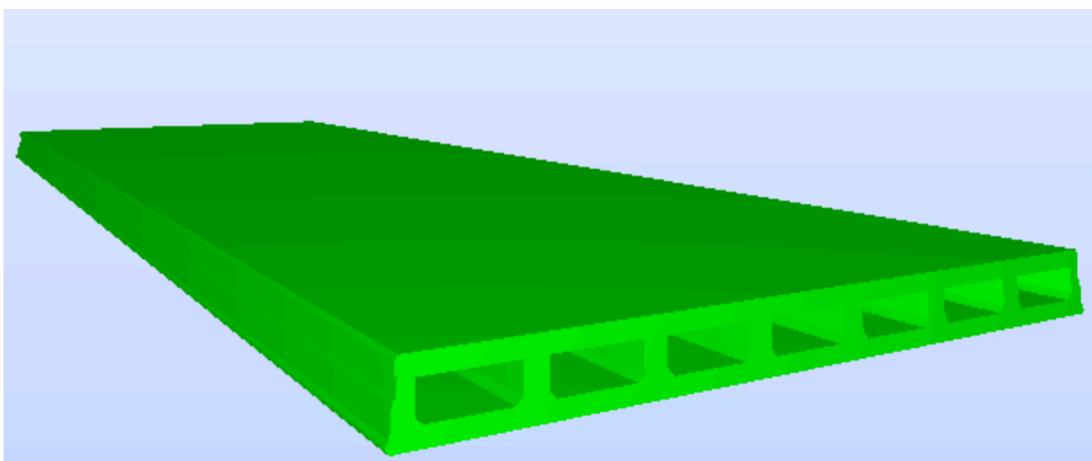
IfcQuantityVolume

Attribute	Implementation agreements
Name	IfcLabel = STRING = "Gross Volume"
Description	Total volume (+void)
Unit	<Open>
VolumeValue	IfcVolumeMeasure

APPENDIX F

PART-21 TEST MODELS FOR CONSTRUCTABILITY EXCHANGE MODEL VALIDATION

We created multiple test models for the validation of the constructability assessment exchange model. One of the model was a two story structure with slabs, columns, and beams. The rest of the test models comprised of only one or two building elements such as a hollow-core slab, a flat roof, and a wall. The test files are in the **.ifc** format, and only important features of the slab test model are presented here. The full models and the rest of test models are available upon request.



Sample Part-21 Test File for Slab

```
ISO-10303-21;


HEADER;
FILE_DESCRIPTION(('ViewDefinition[BCAEM]'),'2;1');
FILE_NAME('sample.ifc','2016-06-20T17:09:24',('GT'),('Georgia Tech'),'GT','EbInstanceModel','GT');
FILE_SCHEMA(('IFC2X3'));
ENDSEC;
```

```
DATA;
#1= IFCPERSON('AD','Gatech','GT',$,$,$,$,$);
#2= IFCORGANIZATION('gatech','GT','BCAEM NBIMS Project',$,$);
#3= IFCPERSONANDORGANIZATION(#1,#2,$);
#4= IFCAPPLICATION(#2,'18.0','Tekla Structures','Multi material modeling');
#5= IFCOWNERHISTORY(#3,#4,$,.NOCHANGE.,$,$,$,1329174154);
#6= IFCCARTESIANPOINT((0.,0.,0.));
#7= IFCDIRECTION((1.,0.,0.));
#8= IFCDIRECTION((0.,1.,0.));
#9= IFCDIRECTION((0.,0.,1.));
/*#10= IFCAXIS2PLACEMENT3D(#6,#8,#9);*/
#10= IFCAXIS2PLACEMENT3D(#6,#9,#7);
#11= IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-005,#10,$);
#12= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,*,#11,$,.MODEL_VIEW.,$);
#13= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#11,$,.GRAPH_VIEW.,$);
#14= IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);
#15= IFCSIUNIT(*,.AREAUNIT.,$,.SQUARE_METRE.);
#16= IFCSIUNIT(*,.VOLUMEUNIT.,$,.CUBIC_METRE.);
#17= IFCSIUNIT(*,.MASSUNIT.,.KILO.,.GRAM.);
#18= IFCSIUNIT(*,.TIMEUNIT.,$,.SECOND.);
#19= IFCSIUNIT(*,.PLANEANGLEUNIT.,$,.RADIAN.);
#20= IFCSIUNIT(*,.SOLIDANGLEUNIT.,$,.STERADIAN.);
#21= IFCSIUNIT(*,.THERMODYNAMICTEMPERATUREUNIT.,$,.DEGREE_CELSIUS.);
#22= IFCSIUNIT(*,.LUMINOUSINTENSITYUNIT.,$,.LUMEN.);
#23= IFCUNITASSIGNMENT((#14,#15,#16,#17,#18,#19,#20,#21,#22));

/*Grids*/
#220=IFCCARTESIANPOINT((0.,0.));
#221=IFCCARTESIANPOINT((600.,0.));
#222=IFCCARTESIANPOINT((600.,100.));
#223=IFCCARTESIANPOINT((600.,200.));
#224=IFCCARTESIANPOINT((600.,300.));
#225=IFCCARTESIANPOINT((600.,400.));
#226=IFCCARTESIANPOINT((600.,500.));
#232=IFCCARTESIANPOINT((600.,600.));
```

```
#233=IFCCARTESIANPOINT((600.,700.));
#234=IFCCARTESIANPOINT((600.,800.));
#235=IFCCARTESIANPOINT((600.,900.));
#236=IFCCARTESIANPOINT((600.,1000.));
#238=IFCCARTESIANPOINT((0.,100.));
#239=IFCCARTESIANPOINT((0.,200.));
#240=IFCCARTESIANPOINT((0.,300.));
#241=IFCCARTESIANPOINT((0.,400.));
#242=IFCCARTESIANPOINT((0.,500.));
#243=IFCCARTESIANPOINT((0.,600.));
#244=IFCCARTESIANPOINT((0.,700.));
#245=IFCCARTESIANPOINT((0.,800.));
#246=IFCCARTESIANPOINT((0.,900.));
#247=IFCCARTESIANPOINT((0.,1000.));
#248=IFCCARTESIANPOINT((0.,1000.));
#249=IFCCARTESIANPOINT((100.,1000.));
#250=IFCCARTESIANPOINT((200.,1000.));
#251=IFCCARTESIANPOINT((300.,1000.));
#252=IFCCARTESIANPOINT((400.,1000.));
#253=IFCCARTESIANPOINT((500.,1000.));
#254=IFCCARTESIANPOINT((600.,1000.));
#255=IFCCARTESIANPOINT((100.,0.));
#256=IFCCARTESIANPOINT((200.,0.));
#257=IFCCARTESIANPOINT((300.,0.));
#258=IFCCARTESIANPOINT((400.,0.));
#259=IFCCARTESIANPOINT((500.,0.));
#260=IFCCARTESIANPOINT((600.,0.));

/*X*/
#1000=IFCPOLYLINE((#220,#221));
#1010=IFCPOLYLINE((#238,#222));
#1020=IFCPOLYLINE((#239,#223));
#1040=IFCPOLYLINE((#240,#224));
#1050=IFCPOLYLINE((#241,#225));
#1060=IFCPOLYLINE((#242,#226));
```

```
#1070=IFCPOLYLINE((#243,#232));
#1080=IFCPOLYLINE((#244,#233));
#1090=IFCPOLYLINE((#245,#234));
#1100=IFCPOLYLINE((#246,#235));
#1110=IFCPOLYLINE((#247,#236));
/*Y*/
#1120=IFCPOLYLINE((#220,#248));
#1130=IFCPOLYLINE((#255,#249));
#1140=IFCPOLYLINE((#256,#250));
#1150=IFCPOLYLINE((#257,#251));
#1160=IFCPOLYLINE((#258,#252));
#1170=IFCPOLYLINE((#259,#253));
#1180=IFCPOLYLINE((#260,#254));
#3000=IFCGRIDAXIS('X-1',#1000,.T.);
#3010=IFCGRIDAXIS('X-2',#1010,.T.);
#3020=IFCGRIDAXIS('X-3',#1020,.T.);
#3030=IFCGRIDAXIS('X-4',#1040,.T.);
#3040=IFCGRIDAXIS('X-5',#1050,.T.);
#3050=IFCGRIDAXIS('X-6',#1060,.T.);
#3060=IFCGRIDAXIS('X-7',#1070,.T.);
#3070=IFCGRIDAXIS('X-8',#1080,.T.);
#3080=IFCGRIDAXIS('X-9',#1090,.T.);
#3090=IFCGRIDAXIS('X-10',#1100,.T.);
#3100=IFCGRIDAXIS('X-11',#1110,.T.);
#3110=IFCGRIDAXIS('Y-1',#1120,.T.);
#3120=IFCGRIDAXIS('Y-2',#1130,.T.);
#3130=IFCGRIDAXIS('Y-3',#1140,.T.);
#3140=IFCGRIDAXIS('Y-4',#1150,.T.);
#3150=IFCGRIDAXIS('Y-5',#1160,.T.);
#3160=IFCGRIDAXIS('Y-6',#1170,.T.);
#3170=IFCGRIDAXIS('Y-7',#1180,.T.);
#153=IFCGRID('28GbUq_xr1Lumxdpa0Z$nr',#5,'Grid','Default','ENTITY_GENERIC_GRID',#25,#155,(#3110,#
3120,#3130,#3140,#3150,#3160,#3170),(#3000,#3010,#3020,#3030,#3040,#3050,#3060,#3070,#3080,#3
090,#3100),$);
#155= IFCPRODUCTDEFINITIONSHAPE($,$,(#157));
```

```
#157= IFCSHAPEREPRESENTATION(#12,'FootPrint','GeometricCurveSet',(#156));
#156=
IFCGEOMETRICCURVESET((#1000,#1010,#1020,#1040,#1050,#1060,#1070,#1080,#1090,#1100,#1110,#11
20,#1130,#1140,#1150,#1160,#1170,#1180));

/* SPATIAL HIERARCHY */
#24= IFCPROJECT('3Sj3c8AR52ZwdXihqTohdw',#5,'BCAEM TEST FILE',$,$,$,$,(#11),#23);
#25= IFCLOCALPLACEMENT($,#10);
#26= IFCSITE('3HwgM7aLX79emd5pXF79OG',#5,'TEST SITE',$,$,#25,$,$,.ELEMENT.,$,$,0.,$,$);
#27= IFCLOCALPLACEMENT(#4100,#10);
#28= IFCBUILDING('3EaEtFJ4H0lBtboHdqylV0',#5,'Building 1',$,$,#27,$,'Commercial Building',.ELEMENT.,
100.,$,#349);
#349= IFCPOSTALADDRESS(.OFFICE.,$,$,$,$,$,$,$,$,$);
#29= IFCLOCALPLACEMENT(#27,#10);
#30= IFCBUILDINGSTOREY('3E$rO7SDn3Tuu4mkkNnAKu',#5,'Floor 1','Sample Floor','Spatial Hierarchy
Element',#29,$,'SpaceName',.ELEMENT.,0.);

#214= IFCRELAGGREGATES('3xRnzKqAn1ZBmbkG8EPq3n',#5,$,$,#24,(#26));
#215= IFCRELAGGREGATES('2WjYovfI5AZv7efLa$2zTy',#5,$,$,#26,(#28));
#216= IFCRELAGGREGATES('3SnOvRr1r6aA2z2vt_kKO$',#5,$,$,#28,(#30));
#217= IFCRELCONTAINEDINSPATIALSTRUCTURE('3GzVRjVOzAmuRAEXJuFHq9',#5,$,$,(#153,#50),#30);

/* Extruded Slab with Slab Type */
#3999= IFCVIRTUALGRIDINTERSECTION((#3000,#3110),(0.,0.));
#4000= IFCVIRTUALGRIDINTERSECTION((#3010,#3120),(0.,0.));
#4100= IFCGRIDPLACEMENT(#4000,#3999);

#6000= IFCCARTESIANPOINT((0.0,0.0,0.));
#6001= IFCCARTESIANPOINT((2417.7625,0.0,0.));
#6002= IFCCARTESIANPOINT((2427.531731,9.76923077,0.));
#6003= IFCCARTESIANPOINT((2427.531731,15.76923077,0.));
#6004= IFCCARTESIANPOINT((2427.531731,19.53846154,0.));
#6005= IFCCARTESIANPOINT((2417.7625,29.30769231,0.));
#6006= IFCCARTESIANPOINT((2412.801563,106.3014423,0.));
#6007= IFCCARTESIANPOINT((2404.467188,111.2623798,0.));
```

```
#6008= IFCCARTESIANPOINT((2401.490625,156.3076923,0.));
#6009= IFCCARTESIANPOINT((2409.229688,161.2686298,0.));
#6010= IFCCARTESIANPOINT((2407.245313,191.2326923,0.));
#6011= IFCCARTESIANPOINT((2398.315625,202.3451923,0.));

#6012= IFCCARTESIANPOINT((19.446875,202.3451923,0.));
#6013= IFCCARTESIANPOINT((10.5171875,191.2326923,0.));
#6014= IFCCARTESIANPOINT((8.5328125,161.2686298,0.));
#6015= IFCCARTESIANPOINT((16.271875,156.3076923,0.));
#6016= IFCCARTESIANPOINT((13.2953125,111.2623798,0.));
#6017= IFCCARTESIANPOINT((4.9609375,106.3014423,0.));
#6018= IFCCARTESIANPOINT((0.0,29.30769231,0.));
#6019= IFCCARTESIANPOINT((-9.76923077,19.53846154,0.));
#6020= IFCCARTESIANPOINT((-9.76923077,9.76923077,0.));

#6025= IFCCARTESIANPOINT((2417.7625,0.0,-7000.));
#6026= IFCCARTESIANPOINT((2427.531731,9.76923077,-7000.));
#6027= IFCCARTESIANPOINT((2427.531731,15.76923077,-7000.));
#6028= IFCCARTESIANPOINT((2427.531731,19.53846154,-7000.));
#6029= IFCCARTESIANPOINT((2417.7625,29.30769231,-7000.));
#6030= IFCCARTESIANPOINT((2412.801563,106.3014423,-7000.));
#6031= IFCCARTESIANPOINT((2404.467188,111.2623798,-7000.));
#6032= IFCCARTESIANPOINT((2401.490625,156.3076923,-7000.));
#6033= IFCCARTESIANPOINT((2409.229688,161.2686298,-7000.));
#6034= IFCCARTESIANPOINT((2407.245313,191.2326923,-7000.));
#6036= IFCCARTESIANPOINT((2398.315625,202.3451923,-7000.));

#6024= IFCCARTESIANPOINT((0.0,0.0,-7000.));
#6037= IFCCARTESIANPOINT((19.446875,202.3451923,-7000.));
#6038= IFCCARTESIANPOINT((10.5171875,191.2326923,-7000.));
#6039= IFCCARTESIANPOINT((8.5328125,161.2686298,-7000.));
#6040= IFCCARTESIANPOINT((16.271875,156.3076923,-7000.));
#6041= IFCCARTESIANPOINT((13.2953125,111.2623798,-7000.));
#6042= IFCCARTESIANPOINT((4.9609375,106.3014423,-7000.));
#6043= IFCCARTESIANPOINT((0.0,29.30769231,-7000.));
```

```
#6044= IFCCARTESIANPOINT((-9.76923077,19.53846154,-7000.));
#6045= IFCCARTESIANPOINT((-9.76923077,9.76923077,-7000.));

#6070=
IFCPOLYLOOP((#6000,#6001,#6002,#6004,#6005,#6006,#6007,#6008,#6009,#6010,#6011,#6012,#6013,#
6014,#6015,#6016,#6017,#6018,#6019,#6020));
#6071= IFCFACEOUTERBOUND(#6070,.T.);

#106072= IFCPOLYLOOP((#6260,#6261,#6262,#6263,#6264,#6265));
#106073= IFCFACEBOUND(#106072,.T.);
#106074= IFCPOLYLOOP((#606700,#606800,#606900,#607000,#607100,#607200));
#106075= IFCFACEBOUND(#106074,.T.);
#106012= IFCPOLYLOOP((#607500,#607600,#607700,#607800,#607900,#608000));
#106013= IFCFACEBOUND(#106012,.T.);
#106014= IFCPOLYLOOP((#608200,#608300,#608400,#608500,#608600,#608700));
#106015= IFCFACEBOUND(#106014,.T.);
#106076= IFCPOLYLOOP((#609200,#609300,#609400,#609500,#609600,#609700));
#106077= IFCFACEBOUND(#106076,.T.);
#106078= IFCPOLYLOOP((#619200,#619300,#619400,#619500,#619600,#619700));
#106079= IFCFACEBOUND(#106078,.T.);
#106010= IFCPOLYLOOP((#629200,#629300,#629400,#629500,#629600,#629700));
#106011= IFCFACEBOUND(#106010,.T.);

#6072= IFCFACE((#6071,#106073,#106075,#106013,#106015,#106077,#106079,#106011));
#6075=
IFCPOLYLOOP((#6025,#6026,#6028,#6029,#6030,#6031,#6032,#6033,#6034,#6036,#6037,#6038,#6039,#
6040,#6041,#6042,#6043,#6044,#6045,#6024));
#6076= IFCFACEOUTERBOUND(#6075,.T.);

#116072= IFCPOLYLOOP((#6267,#6268,#6269,#6270,#6271,#6272));
#116073= IFCFACEBOUND(#116072,.T.);
#116074= IFCPOLYLOOP((#60670,#60680,#60690,#60700,#60710,#60720));
#116075= IFCFACEBOUND(#116074,.T.);
#116012= IFCPOLYLOOP((#60750,#60760,#60770,#60780,#60790,#60800));
#116013= IFCFACEBOUND(#116012,.T.);
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```
#116014= IFCPOLYLOOP((#60820,#60830,#60840,#60850,#60860,#60870));
#116015= IFCFACEBOUND(#116014,.T.);
#116076= IFCPOLYLOOP((#60920,#60930,#60940,#60950,#60960,#60970));
#116077= IFCFACEBOUND(#116076,.T.);
#116078= IFCPOLYLOOP((#61920,#61930,#61940,#61950,#61960,#61970));
#116079= IFCFACEBOUND(#116078,.T.);
#116010= IFCPOLYLOOP((#62920,#62930,#62940,#62950,#62960,#62970));
#116011= IFCFACEBOUND(#116010,.T.);
#6080= IFCFACE((#6076,#116073,#116075,#116013,#116015,#116077,#116079,#116011));

#6087= IFCPOLYLOOP((#6000,#6001,#6025,#6024));
#6088= IFCFACEOUTERBOUND(#6087,.T.);
#6089= IFCFACE((#6088));

#6084= IFCPOLYLOOP((#6011,#6012,#6037,#6036));
#6085= IFCFACEOUTERBOUND(#6084,.T.);
#6086= IFCFACE((#6085));

#6187= IFCPOLYLOOP((#6001,#6002,#6026,#6025));
#6185= IFCFACEOUTERBOUND(#6187,.T.);
#6186= IFCFACE((#6185));

#6188= IFCPOLYLOOP((#6002,#6004,#6028,#6026));
#6189= IFCFACEOUTERBOUND(#6188,.T.);
#6190= IFCFACE((#6189));

#6191= IFCPOLYLOOP((#6004,#6005,#6029,#6028));
#6192= IFCFACEOUTERBOUND(#6191,.T.);
#6193= IFCFACE((#6192));

#6194= IFCPOLYLOOP((#6005,#6006,#6030,#6029));
#6195= IFCFACEOUTERBOUND(#6194,.T.);
#6196= IFCFACE((#6195));

#6197= IFCPOLYLOOP((#6006,#6007,#6031,#6030));
```

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#6198= IFCFACEOUTERBOUND(#6197,.T.);
#6199= IFCFACE((#6198));

#6200= IFCPOLYLOOP((#6007,#6008,#6032,#6031));
#6201= IFCFACEOUTERBOUND(#6200,.T.);
#6202= IFCFACE((#6201));

#6203= IFCPOLYLOOP((#6008,#6009,#6033,#6032));
#6204= IFCFACEOUTERBOUND(#6203,.T.);
#6205= IFCFACE((#6204));

#6206= IFCPOLYLOOP((#6009,#6010,#6034,#6033));
#6207= IFCFACEOUTERBOUND(#6206,.T.);
#6208= IFCFACE((#6207));

#6209= IFCPOLYLOOP((#6010,#6011,#6036,#6034));
#6210= IFCFACEOUTERBOUND(#6209,.T.);
#6211= IFCFACE((#6210));

#6212= IFCPOLYLOOP((#6012,#6013,#6038,#6037));
#6213= IFCFACEOUTERBOUND(#6212,.T.);
#6214= IFCFACE((#6213));

#6215= IFCPOLYLOOP((#6013,#6014,#6039,#6038));
#6216= IFCFACEOUTERBOUND(#6215,.T.);
#6217= IFCFACE((#6216));

#6218= IFCPOLYLOOP((#6014,#6015,#6040,#6039));
#6219= IFCFACEOUTERBOUND(#6218,.T.);
#6220= IFCFACE((#6219));

#6221= IFCPOLYLOOP((#6015,#6016,#6041,#6040));
#6222= IFCFACEOUTERBOUND(#6221,.T.);
#6223= IFCFACE((#6222));
```

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#6224= IFCPOLYLOOP((#6016,#6017,#6042,#6041));
#6225= IFCFACEOUTERBOUND(#6224,.T.);
#6226= IFCFACE((#6225));

#6227= IFCPOLYLOOP((#6017,#6018,#6043,#6042));
#6228= IFCFACEOUTERBOUND(#6227,.T.);
#6229= IFCFACE((#6228));

#6230= IFCPOLYLOOP((#6018,#6019,#6044,#6043));
#6231= IFCFACEOUTERBOUND(#6230,.T.);
#6232= IFCFACE((#6231));

#6233= IFCPOLYLOOP((#6019,#6020,#6045,#6044));
#6234= IFCFACEOUTERBOUND(#6233,.T.);
#6235= IFCFACE((#6234));

#6236= IFCPOLYLOOP((#6020,#6000,#6024,#6045));
#6237= IFCFACEOUTERBOUND(#6236,.T.);
#6238= IFCFACE((#6237));

#6289= IFCPOLYLOOP((#6267,#6260,#6261,#6268));
#6239= IFCFACEOUTERBOUND(#6289,.T.);
#6240= IFCFACE((#6239));

#6298= IFCPOLYLOOP((#6270,#6271,#6264,#6263));
#6241= IFCFACEOUTERBOUND(#6298,.T.);
#6242= IFCFACE((#6241));

#6243= IFCPOLYLOOP((#6260,#6265,#6272,#6267));
#6244= IFCFACEOUTERBOUND(#6243,.T.);
#6245= IFCFACE((#6244));

#6246= IFCPOLYLOOP((#6265,#6264,#6271,#6272));
#6247= IFCFACEOUTERBOUND(#6246,.T.);
#6248= IFCFACE((#6247));
```

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#6249= IFCPOLYLOOP((#6264,#6263,#6270,#6271));
#6250= IFCFACEOUTERBOUND(#6249,.T.);
#6251= IFCFACE((#6250));

#6252= IFCPOLYLOOP((#6263,#6262,#6269,#6270));
#6253= IFCFACEOUTERBOUND(#6252,.T.);
#6254= IFCFACE((#6253));

#6255= IFCPOLYLOOP((#6262,#6261,#6268,#6269));
#6256= IFCFACEOUTERBOUND(#6255,.T.);
#6257= IFCFACE((#6256));

#607300= IFCPOLYLOOP((#606700,#607200,#60720,#60670));
#6557= IFCFACEOUTERBOUND(#607300,.T.);
#6558= IFCFACE((#6557));

#607301= IFCPOLYLOOP((#607200,#607100,#60710,#60720));
#6559= IFCFACEOUTERBOUND(#607301,.T.);
#6560= IFCFACE((#6559));

#607302= IFCPOLYLOOP((#607100,#607000,#60700,#60710));
#6561= IFCFACEOUTERBOUND(#607302,.T.);
#6562= IFCFACE((#6561));

#607303= IFCPOLYLOOP((#606700,#606800,#60680,#60670));
#6563= IFCFACEOUTERBOUND(#607303,.T.);
#6564= IFCFACE((#6563));

#607304= IFCPOLYLOOP((#607000,#606900,#60690,#60700));
#6565= IFCFACEOUTERBOUND(#607304,.T.);
#6566= IFCFACE((#6565));

#607305= IFCPOLYLOOP((#606900,#606800,#60680,#60690));
#6567= IFCFACEOUTERBOUND(#607305,.T.);
#6568= IFCFACE((#6567));
```

```
#60802= IFCPOLYLOOP((#607500,#607600,#60760,#60750));
#6569= IFCFACEOUTERBOUND(#60802,.T.);
#6570= IFCFACE((#6569));

#60803= IFCPOLYLOOP((#607900,#60790,#60780,#607800));
#6571= IFCFACEOUTERBOUND(#60803,.T.);
#6572= IFCFACE((#6571));

#608100= IFCPOLYLOOP((#607500,#608000,#60800,#60750));
#6573= IFCFACEOUTERBOUND(#608100,.T.);
#6574= IFCFACE((#6573));

#60801= IFCPOLYLOOP((#608000,#607900,#60790,#60800));
#6575= IFCFACEOUTERBOUND(#60801,.T.);
#6576= IFCFACE((#6575));

#60804= IFCPOLYLOOP((#607700,#607800,#60780,#60770));
#6579= IFCFACEOUTERBOUND(#60804,.T.);
#6580= IFCFACE((#6579));

#60805= IFCPOLYLOOP((#607700,#607600,#60760,#60770));
#6581= IFCFACEOUTERBOUND(#60805,.T.);
#6582= IFCFACE((#6581));

#60872= IFCPOLYLOOP((#608200,#608300,#60830,#60820));
#6583= IFCFACEOUTERBOUND(#60872,.T.);
#6584= IFCFACE((#6583));

#60875= IFCPOLYLOOP((#608300,#608400,#60840,#60830));
#6585= IFCFACEOUTERBOUND(#60875,.T.);
#6586= IFCFACE((#6585));

#60876= IFCPOLYLOOP((#608400,#608500,#60850,#60840));
#6587= IFCFACEOUTERBOUND(#60876,.T.);
#6588= IFCFACE((#6587));
```

```
#60873= IFCPOLYLOOP((#608600,#608500,#60850,#60860));
#6589= IFCFACEOUTERBOUND(#60873,.T.);
#6590= IFCFACE((#6589));

#608900= IFCPOLYLOOP((#608600,#608700,#60870,#60860));
#6591= IFCFACEOUTERBOUND(#608900,.T.);
#6592= IFCFACE((#6591));

#60871= IFCPOLYLOOP((#608700,#608200,#60820,#60870));
#6593= IFCFACEOUTERBOUND(#60871,.T.);
#6594= IFCFACE((#6593));

#609800= IFCPOLYLOOP((#609200,#609300,#60930,#60920));
#6595= IFCFACEOUTERBOUND(#609800,.T.);
#6596= IFCFACE((#6595));

#60971= IFCPOLYLOOP((#609300,#609400,#60940,#60930));
#6597= IFCFACEOUTERBOUND(#60971,.T.);
#6598= IFCFACE((#6597));

#60972= IFCPOLYLOOP((#609400,#609500,#60950,#60940));
#6599= IFCFACEOUTERBOUND(#60972,.T.);
#6600= IFCFACE((#6599));

#61873= IFCPOLYLOOP((#609600,#609500,#60950,#60960));
#6601= IFCFACEOUTERBOUND(#61873,.T.);
#6602= IFCFACE((#6601));

#60973= IFCPOLYLOOP((#609600,#609700,#60970,#60960));
#6603= IFCFACEOUTERBOUND(#60973,.T.);
#6604= IFCFACE((#6603));

#60974= IFCPOLYLOOP((#609700,#609200,#60920,#60970));
#6605= IFCFACEOUTERBOUND(#60974,.T.);
#6606= IFCFACE((#6605));
```

```
#61980= IFCPOLYLOOP((#619200,#619300,#61930,#61920));
#6607= IFCFACEOUTERBOUND(#61980,.T.);
#6608= IFCFACE((#6607));

#61971= IFCPOLYLOOP((#619300,#619400,#61940,#61930));
#6609= IFCFACEOUTERBOUND(#61971,.T.);
#6610= IFCFACE((#6609));

#61972= IFCPOLYLOOP((#619400,#619500,#61950,#61940));
#6611= IFCFACEOUTERBOUND(#61972,.T.);
#6612= IFCFACE((#6611));

#61973= IFCPOLYLOOP((#619600,#619500,#61950,#61960));
#6613= IFCFACEOUTERBOUND(#61973,.T.);
#6614= IFCFACE((#6613));

#61974= IFCPOLYLOOP((#619600,#619700,#61970,#61960));
#6615= IFCFACEOUTERBOUND(#61974,.T.);
#6616= IFCFACE((#6615));

#61975= IFCPOLYLOOP((#619700,#619200,#61920,#61970));
#6617= IFCFACEOUTERBOUND(#61975,.T.);
#6618= IFCFACE((#6617));

#629800= IFCPOLYLOOP((#629200,#629300,#62930,#62920));
#6619= IFCFACEOUTERBOUND(#629800,.T.);
#6620= IFCFACE((#6619));

#62971= IFCPOLYLOOP((#629300,#629400,#62940,#62930));
#6621= IFCFACEOUTERBOUND(#62971,.T.);
#6622= IFCFACE((#6621));

#62972= IFCPOLYLOOP((#629400,#629500,#62950,#62940));
#6623= IFCFACEOUTERBOUND(#62972,.T.);
#6624= IFCFACE((#6623));
```

```
#62973= IFCPOLYLOOP((#629600,#629500,#62950,#62960));
#6625= IFCFACEOUTERBOUND(#62973,.T.);
#6626= IFCFACE((#6625));

#62974= IFCPOLYLOOP((#629600,#629700,#62970,#62960));
#6627= IFCFACEOUTERBOUND(#62974,.T.);
#6628= IFCFACE((#6627));

#62975= IFCPOLYLOOP((#629700,#629200,#62920,#62970));
#6629= IFCFACEOUTERBOUND(#62975,.T.);
#6630= IFCFACE((#6629));

#6090=
IFCCLOSEDSHELL((#6072,#6080,#6089,#6086,#6186,#6190,#6193,#6196,#6199,#6202,#6205,#6208,#621
1,#6214,#6217,#6220,#6223,#6226,#6229,#6232,#6235,#6238,#6240,#6242,#6245,#6248,#6251,#6254,#
6257,#6558,#6560,#6562,#6564,#6566,#6568,#6570,#6572,#6574,#6576,#6580,#6582,#6584,#6586,#658
8,#6590,#6592,#6594,#6596,#6598,#6600,#6602,#6604,#6606,#6608,#6610,#6612,#6614,#6616,#6618,#
6620,#6622,#6624,#6626,#6628,#6630));

#6091= IFCFACETEDBREP(#6090);
#31= IFCCARTESIANPOINT((0.,0.,0.));
#32= IFCDIRECTION((1.,0.,0.));
#43= IFCDIRECTION((0.,-1.,0.));
#44= IFCCARTESIANPOINT((0.,0.,0.));
#45= IFCAXIS2PLACEMENT3D(#44,#43,#32);
#46= IFCLOCALPLACEMENT(#27,#45);
#47= IFCSHAPEREPRESENTATION(#12,'Body','Brep',(#6091));
#49= IFCPRODUCTDEFINITIONSHAPE($,$,(#47));
#4101= IFCLOCALPLACEMENT(#27,#45);
#50= IFCSLAB('1FEI3U000sVZ4pCZanDpCq',#5,'Slab','500X1000','Flat slab
piece',#4101,#49,'TS_4201',.FLOOR.);
#51=
IFCSLABTYPE('3tzijQMNHA8QMweTh8UocH',#5,'500X1000',$,'Slab',$,(#75),$,'FLOOR',.NOTDEFINED.);
#75= IFCREPRESENTATIONMAP(#10,#47);
```

```
/*Hollows*/
/*H1*/
#6260= IFCCARTESIANPOINT((70.0,50.0,0.));
#6261= IFCCARTESIANPOINT((300.,50.0,0.));
#6262= IFCCARTESIANPOINT((320.,70.,0.));
#6263= IFCCARTESIANPOINT((320.,150.,0.));
#6264= IFCCARTESIANPOINT((50.,150.,0.));
#6265= IFCCARTESIANPOINT((50.,70.,0.));
#6268= IFCCARTESIANPOINT((300.,50.0,-7000.));
#6269= IFCCARTESIANPOINT((320.,70.,-7000.));
#6270= IFCCARTESIANPOINT((320.,150.,-7000.));
#6267= IFCCARTESIANPOINT((70.0,50.0,-7000.));
#6271= IFCCARTESIANPOINT((50.,150.,-7000.));
#6272= IFCCARTESIANPOINT((50.,70.,-7000.));

/*H2*/
#606700= IFCCARTESIANPOINT((410.0,50.0,0.));
#606800= IFCCARTESIANPOINT((640.,50.,0.));
#606900= IFCCARTESIANPOINT((660.,70.,0.));
#607000= IFCCARTESIANPOINT((660.,150.,0.));
#607100= IFCCARTESIANPOINT((390.,150.,0.));
#607200= IFCCARTESIANPOINT((390.,70.,0.));
#60670= IFCCARTESIANPOINT((410.0,50.,-7000.));
#60680= IFCCARTESIANPOINT((640.,50.,-7000.));
#60690= IFCCARTESIANPOINT((660.,70.,-7000.));
#60700= IFCCARTESIANPOINT((660.,150.,-7000.));
#60710= IFCCARTESIANPOINT((390.,150.,-7000.));
#60720= IFCCARTESIANPOINT((390.,70.,-7000.));
/*H3*/
#607500= IFCCARTESIANPOINT((750.0,50.0,0.));
#607600= IFCCARTESIANPOINT((980.,50.0,0.));
#607700= IFCCARTESIANPOINT((1000.,70.,0.));
#607800= IFCCARTESIANPOINT((1000.,150.,0.));
#607900= IFCCARTESIANPOINT((730.,150.,0.));
#608000= IFCCARTESIANPOINT((730.,70.,0.));
```

```
#60750= IFCCARTESIANPOINT((750.0,50.0,-7000.));
#60760= IFCCARTESIANPOINT((980.,50.0,-7000.));
#60770= IFCCARTESIANPOINT((1000.,70.,-7000.));
#60780= IFCCARTESIANPOINT((1000.,150.,-7000.));
#60790= IFCCARTESIANPOINT((730.,150.,-7000.));
#60800= IFCCARTESIANPOINT((730.,70.,-7000.));

/*H4*/
#608200= IFCCARTESIANPOINT((1090.0,50.0,0.));
#608300= IFCCARTESIANPOINT((1320.,50.0,0.));
#608400= IFCCARTESIANPOINT((1340.,70.,0.));
#608500= IFCCARTESIANPOINT((1340.,150.,0.));
#608600= IFCCARTESIANPOINT((1070.,150.,0.));
#608700= IFCCARTESIANPOINT((1070.,70.,0.));
#60820= IFCCARTESIANPOINT((1090.0,50.0,-7000.));
#60830= IFCCARTESIANPOINT((1320.,50.0,-7000.));
#60840= IFCCARTESIANPOINT((1340.,70.,-7000.));
#60850= IFCCARTESIANPOINT((1340.,150.,-7000.));
#60860= IFCCARTESIANPOINT((1070.,150.,-7000.));
#60870= IFCCARTESIANPOINT((1070.,70.,-7000.));

/*H5*/
#609200= IFCCARTESIANPOINT((1430.0,50.0,0.));
#609300= IFCCARTESIANPOINT((1660.,50.0,0.));
#609400= IFCCARTESIANPOINT((1680.,70.,0.));
#609500= IFCCARTESIANPOINT((1680.,150.,0.));
#609600= IFCCARTESIANPOINT((1410.,150.,0.));
#609700= IFCCARTESIANPOINT((1410.,70.,0.));
#60920= IFCCARTESIANPOINT((1430.0,50.0,-7000.));
#60930= IFCCARTESIANPOINT((1660.,50.0,-7000.));
#60940= IFCCARTESIANPOINT((1680.,70.,-7000.));
#60950= IFCCARTESIANPOINT((1680.,150.,-7000.));
#60960= IFCCARTESIANPOINT((1410.,150.,-7000.));
#60970= IFCCARTESIANPOINT((1410.,70.,-7000.));
```

```
/*H6*/
#619200= IFCCARTESIANPOINT((1770.0,50.0,0.));
#619300= IFCCARTESIANPOINT((2000.,50.0,0.));
#619400= IFCCARTESIANPOINT((2020.,70.,0.));
#619500= IFCCARTESIANPOINT((2020.,150.,0.));
#619600= IFCCARTESIANPOINT((1750.,150.,0.));
#619700= IFCCARTESIANPOINT((1750.,70.,0.));
#61920= IFCCARTESIANPOINT((1770.0,50.0,-7000.));
#61930= IFCCARTESIANPOINT((2000.,50.0,-7000.));
#61940= IFCCARTESIANPOINT((2020.,70.,-7000.));
#61950= IFCCARTESIANPOINT((2020.,150.,-7000.));
#61960= IFCCARTESIANPOINT((1750.,150.,-7000.));
#61970= IFCCARTESIANPOINT((1750.,70.,-7000.));

/*H7*/
#629200= IFCCARTESIANPOINT((2110.0,50.0,0.));
#629300= IFCCARTESIANPOINT((2340.,50.0,0.));
#629400= IFCCARTESIANPOINT((2360.,70.,0.));
#629500= IFCCARTESIANPOINT((2360.,150.,0.));
#629600= IFCCARTESIANPOINT((2090.,150.,0.));
#629700= IFCCARTESIANPOINT((2090.,70.,0.));
#62920= IFCCARTESIANPOINT((2110.0,50.0,-7000.));
#62930= IFCCARTESIANPOINT((2340.,50.0,-7000.));
#62940= IFCCARTESIANPOINT((2360.,70.,-7000.));
#62950= IFCCARTESIANPOINT((2360.,150.,-7000.));
#62960= IFCCARTESIANPOINT((2090.,150.,-7000.));
#62970= IFCCARTESIANPOINT((2090.,70.,-7000.));

/* MATERIAL */
#87= IFCMATERIAL('CONCRETE/5000');
#2240= IFCRELASSOCIATESMATERIAL('3g83wpL112Vxbx1qzLBqSL',#5,$,$,(#50),#87);
#2230= IFCRELDEFINESBYTYPE('0f8EmwlRf85RE973_p$GLQ',#5,$,$,(#50),#51);

/*Area*/
#70001= IFCELEMENTQUANTITY('36OilPtieson0g0aeArkTlH3',#5,'Slab Area',$,$,(#70002));
```

```
#70002= IFCQUANTITYAREA('Area',$,#15,3000.);
#70003= IFCRELDEFINESBYPROPERTIES('57AreAtieson0g0aeArkTlH3',#5,'Element Area',$,(#50),#70001);

/*Approval*/
#90001= IFCAPPROVAL($,IFCCALENDARDATE('3,5,2016'),'Approved',$,$,'Approval','Apprv');
#90010= IFCRELASSOCIATESAPPROVAL('20KilPtieson0g0aeArkTl9Y',#5,$,$,(#50),#90001);
#90012= IFCAPPROVALACTORRELATIONSHIP(#3,#90001,#90013);
#90013= IFCACTORROLE(.CONSTRUCTIONMANAGER.,$,$);

/*Actor*/
#90021= IFCACTOR('40Aacttieson0g0aeArkTlH3',#5,$,$,'SlabActor',#3);
#90022= IFCRELASSIGNSTOACTOR('50Aacttieson0g0aeArkTlH3',#5,$,$,(#50),$,#90021,$);

/*Library*/
#90031= IFCRELASSOCIATESLIBRARY('73Aacttieson0g0aeArkTlH3',#5,$,$,(#50),#90032);
#90032= IFCLIBRARYREFERENCE($,$,'Library');
#90033= IFCLIBRARYINFORMATION(('Libr'),('V1'),$,$,(#90032));

/*Construction Type*/
#100001312= IFCRELDEFINESBYPROPERTIES('00TllPtieson0g0aeArkTlH3',#5,$,$,(#50),#100001412);
#100001412= IFCPROPERTYSET('85PllPtieson0g0aeArkTlH3',#5,'Pset_ElementGeneraL',$,(#100001513));
#100001513= IFCPROPERTYSINGLEVALUE('Construction Type', $, IFCIDENTIFIER('Precast slab with in-situ
topping'),$);

ENDSEC;
END-ISO-10303-21;
```

APPENDIX G

EXPERIMENTAL STUDY

Section A: Demographic Questionnaire

Date: ___/___/2016

Subject Number: ______

1. What is your level of degree?
☐High school diploma
☐Bachelor
☐Masters
☐PhD

2. What is the job title of your current position?
____

3. Please briefly explain your role and responsibility in this job:
____
____
____

4. Years of experience in construction:
☐Less than 1year
☐Between 1 and 5 years
☐Between 6 and 10 years
☐More than 10 years

5. Have you ever worked on any commercial construction project?
☐ Yes,
How many years of experience in commercial projects? -- -- -- -- -- -- -- -- -- -- -- --
In which states? -- - -- -- - --
List type of commercial buildings you have worked on:
-- ---- -- -- -- -- -- -- -- -- -- -- --
-- -- -- -- -- -- -- -- -- -- -- -- -- ---- --
☐No

SECTION B: Post Experiment Questionnaire

Date: ___/___/2016

Subject Number: ______

The aim of this questionnaire is to capture your satisfaction and feedback with the usability of the experiment approach in terms of the BIM-based constructability assessment exchange model (BCAEM).

To as great a degree as possible, think about all the tasks and questions and provide accurate responses to them.

Thank you!

Questionnaire

1. I can <u>easily improve</u> the constructability of designs using the constructability assessment model.

☐ Strongly disagree ☐ Disagree ☐ Neither agree or disagree ☐ Agree ☐ Strongly agree

2. I can <u>quickly explore</u> the constructability of design alternatives using the constructability assessment model.

☐ Strongly disagree ☐ Disagree ☐ Neither agree or disagree ☐ Agree ☐ Strongly agree

3. I can <u>learn more</u> about the constructability of designs using the constructability assessment model.

☐ Strongly disagree ☐ Disagree ☐ Neither agree or disagree ☐ Agree ☐ Strongly agree

4. I can <u>create more constructible designs</u> using the constructability assessment model.

☐ Strongly disagree ☐ Disagree ☐ Neither agree or disagree ☐ Agree ☐ Strongly agree

5. I believe the constructability assessment model has <u>values to designers</u>.

☐ Strongly disagree ☐ Disagree ☐ Neither agree or disagree ☐ Agree ☐ Strongly agree

6. What are the advantages and disadvantages of the constructability assessment model?

-- ---- -- -- -- -- -- -- -- -- -- -- -- -- -- -

- -- -- -- -- -- -- -- -- -- -- ---- -- -- -- -- -- -- -- -- ---- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --

-- -- -- -- -- -- -- ---- ---- -- -- -- -- -- --

-- -- -- ---- ---- --

7. How to improve the constructability assessment model?

REFERENCES

Aci 2012. Information Delivery Manual (IDM) for Cast-in-place Concrete (ACI 131.1 Version 1.0). ACI Committee 131.

Al Khalil, M. I. 2002. Selecting the appropriate project delivery method using AHP. *International journal of project management,* 20**,** 469-474.

Albattah, M. A., Goodrum, P. M. & Taylor, T. R. 2015. Demographic influences on construction craft shortages in the US and Canada.

An, S.-H., Kim, G.-H. & Kang, K.-I. 2007. A case-based reasoning cost estimating model using experience by analytic hierarchy process. *Building and Environment,* 42**,** 2573-2579.

Autodesk 2007. Maintaining BIM Integrity in the Structural Engineering Office. *REVIT® STRUCTURE.* https://i-theses.com/nl/images/stories/pdf/bim_integrity_in_structural_engineering_feb07%5B1%5D.pdf: Autodesk.

Ballal, T. 1999. *The use of artificial neural networks for modelling buildability in preliminary structural design.* © Tabarak MA Ballal.

Bca, B. a. C. A. 2014. The Code of Practice on Buildability. Building and Construction Authority.

Bhushan, N. & Rai, K. 2007. *Strategic decision making: applying the analytic hierarchy process*, Springer Science & Business Media.

Bjaaland, A., Bell, H. V., Bjørkhaug, L. & Grant, R. 2012. National BIM Standard - United StatesTM Version 2. National Institute of Building Sciences buildingSMART allianceTM.

Brown, J. D. 2009. Choosing the right type of rotation in PCA and EFA. *JALT Testing & Evaluation SIG Newsletter,* 13**,** 20-25.

Buildingsmart. 2015a. *IFC Overview summary* [Online]. buildingSMART. [Accessed May, 28 2015].

Buildingsmart. 2015b. *ifcDoc Tool Summary* [Online]. [Accessed April, 4 2015].

Buildingsmart. 2015c. *Industry Foundation Class (IFC) data model* [Online]. http://www.buildingsmart.org/standards/technical-vision/open-standards-101/. [Accessed April, 4 2015].

Buildingsmart. 2015d. *Information Exchange Projects* [Online]. [Accessed June, 27 2015].

Burt, B. A. 2009. BIM interoperability, the promise and the reality. *Structure Magazine.* http://www.structuremag.org/wp-content/uploads/2014/08/C-Technology-Burt-Dec091.pdf.

Chao, M., Qiping, S., Jun, W. & Chen, L. 2013. A BIM-enabled Estimating Framework of Embodied Emissions of Building Materials for Optimization in Design Stage: A Case Study. *International Journal of Digital Content Technology & its Applications,* 7.

Charles Eastman, Tim Chipman & Keller, C. 2014. PRECAST CONCRETE NATIONAL BIM STANDARD - PHASE III-C. Prestressed Concrete Institute and Charles Pankow Foundation.

Cheung, F. K., Kuen, J. L. F. & Skitmore, M. 2002. Multi-criteria evaluation model for the selection of architectural consultants. *Construction Management & Economics,* 20**,** 569-580.

Cheung, S.-O., Lam, T.-I., Leung, M.-Y. & Wan, Y.-W. 2001. An analytical hierarchy process based procurement selection method. *Construction Management & Economics,* 19**,** 427-437.

Chipman, T. 2012. IFCDOC Usage Guide http://www.buildingsmart-tech.org/specifications/specification-tools/ifcdoc-tool/ifcdoc-help-page-section: ifcDoc Tool Summary — Welcome to buildingSMART-Tech.org.

Cii 1986. Constructability: a primer (**Construction Industry Institute)**.

Comrey, A. L. & Lee, H. B. 2013. *A first course in factor analysis*, Psychology Press.

Dai, J., Goodrum, P. M. & Maloney, W. F. 2009. Construction craft workers' perceptions of the factors affecting their productivity. *Journal of Construction Engineering and Management,* 135**,** 217-226.

Dbl, D. B. L. 2013. *Final Steel Detailing* [Online]. [Accessed July, 21st 2015].

East, E. W. 2007. Construction operations building information exchange (Cobie): Requirements definition and pilot implementation standard. DTIC Document.

Eastman, C., Jeong, Y. S., Sacks, R. & Kaner, I. 2009a. Exchange model and exchange object concepts for implementation of national BIM standards. *Journal of Computing in Civil Engineering,* 24**,** 25-34.

Eastman, C., Panushev, I., Sacks, R., Venugopal, M., Aram, V., See, R. & Yagmur, E. 2011a. A guide for development and preparation of a national bim exchange standard. *buildingSMART Report.*< http://www/. *buildingsmartalliance. org/client/assets/files/bsa/IDM-MVD_Development_Guide_v4. pdf>(Jan. 09, 2012)*.

Eastman, C., Sacks, R., Panushev, I., Aram, V. & Yagmur, E. 2009b. Information Delivery Manual for Precast Concrete. *PCI-Charles Pankow Foundation.*

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. 2011b. *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*, John Wiley & Sons.

Fischer, M. 1991a. Constructability input to preliminary design of reinforced concrete structures. http://cife.stanford.edu/node/561: Stanford University.

Fischer, M. 1991b. Constructibility input to preliminary design of reinforced concrete structures. *Technical Report #64.* CIFE - Center for Integrated Facility Engineering, Stanford University.

Fischer, M. & Tatum, C. B. 1997. Characteristics of design-relevant constructability knowledge. *Journal of Construction Engineering and Management,* 123**,** 253-260.

Flager, F. & Haymaker, J. 2007. A comparison of multidisciplinary design, analysis and optimization processes in the building construction and aerospace industries. *In:* CITESEER (ed.) *in 24th international conference on information technology in construction.*

Floyd, F. J. & Widaman, K. F. 1995. Factor analysis in the development and refinement of clinical assessment instruments. *Psychological assessment,* 7**,** 286.

Fong, P. S.-W. & Choi, S. K.-Y. 2000. Final contractor selection using the analytical hierarchy process. *Construction Management & Economics,* 18**,** 547-557.

Gable, G. G. 1994. Integrating case study and survey research methods: an example in information systems. *European journal of information systems,* 3**,** 112-126.

Gilleard, J. D. & Wong Yat-Lung, P. 2004. Benchmarking facility management: applying analytic hierarchy process. *Facilities,* 22**,** 19-25.

Gonzales, D. 2013. Workforce trends in the construction industry. Zurich American Insurance Corporation.

Gorsuch, R. 1983. Factor analysis, 2nd. *Hillsdale, NJ: LEA*.

Grošelj, P., Malovrh, Š. P. & Stirn, L. Z. 2011. Methods based on data envelopment analysis for deriving group priorities in analytic hierarchy process. *Central European Journal of Operations Research,* 19**,** 267-284.

Hackos, J. T., Rubin, J., Dumas, J. S., Redish, J. C. & Nielsen, J. 1995. Handbook of Usability Testing. JSTOR.

Hanlon, E. J. & Sanvido, V. E. 1995. Constructability information classification scheme. *Journal of construction engineering and management,* 121**,** 337-345.

Hassan, S. A. & Bakar, K. A. 2008. Exploratory Factor Analysis versus Confirmatory Factor Analysis. *Teachers' Learning, Curriculum Innovations and Knowledge Applications.* Universiti Putra Malaysia Press.

Horn, A. 2015. *Integrating constructability into conceptual structural design and optimization.* Massachusetts Institute of Technology.

Iug/Idmc 2010. Information Delivery Manual Guide to Components and Development Methods http://iug.buildingsmart.org/idms/development/IDMC_004_1_2.pdf: BuidlingSMART International.

Jarkas, A. M. 2012. Analysis and measurement of buildability factors influencing rebar installation labor productivity of in situ reinforced concrete walls. *Journal of Architectural Engineering,* 18**,** 52-60.

Jarkas, A. M. 2015. Effect of Buildability on Labor Productivity: A Practical Quantification Approach. *Journal of Construction Engineering and Management*, 06015002.

Jeong, Y.-S., Eastman, C., Sacks, R. & Kaner, I. 2009. Benchmark tests for BIM data exchanges of precast concrete. *Automation in construction,* 18**,** 469-484.

Jiang, L. & Leicht, R. M. 2014. Automated rule-based constructability checking: Case study of formwork. *Journal of Management in Engineering*.

Jiang, L., Leicht, R. M. & Messner, J. I. 2015. Towards Automated Constructability Checking: A Case Study of Aligning Design Information with Formwork Decisions. *Computing in Civil Engineering***,** 531-539.

Jöreskog, K. G. & Sörbom, D. 1989. *LISREL 7 user's reference guide*, Scientific Software.

Kannan, M. R. & Santhi, M. H. 2013. Constructability Assessment of Climbing Formwork Systems Using Building Information Modeling. *Procedia Engineering,* 64**,** 1129-1138.

Kuo, V. & Wium, J. A. 2014. The management of constructability knowledge in the building industry through lessons learnt programmes. *Journal of the South African Institution of Civil Engineering,* 56**,** 20-27.

Lam, P. T. I., Chan, A. P. C., Wong, F. K. W. & Wong, F. W. H. 2007. Constructability rankings of construction systems based on the analytical hierarchy process. *Journal of architectural engineering,* 13**,** 36-43.

Lam, P. T. I., Wong, F. W. H. & Chan, A. P. C. 2006. Contributions of designers to improving buildability and constructability. *Design Studies,* 27**,** 457-479.

Lee, S., Degraw, J. W., Bahnfleth, W., Leicht, R. M. & Messner, J. I. BIM-based Processes and Standardized Information Exchanges for Multizone Airflow Analysis. 2014 ASHRAE/IBPSA-USA Building Simulation Conference, 2014. ASHRAE., 129-136.

Lee, Y. C. 2015. *Rule logic and its validation framework of model view definitions for building information modeling.* PhD, Georgia Institute of Technology.

Liu, J., Shahi, A., Haas, C. T., Goodrum, P. & Caldas, C. H. 2014. Validation methodologies and their impact in construction productivity research. *Journal of Construction Engineering and Management,* 140**,** 04014046.

Macleamy, P. 2004. MacLeamy Curve. *Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation (WP-1202)*.

Mahdi, I. M., Riley, M. J., Fereig, S. M. & Alex, A. P. 2002. A multi-criteria approach to contractor selection. *Engineering Construction and Architectural Management,* 9**,** 29-37.

Mcdowall, R. 2008. Constructability. *Institution of Professional Engineers New Zealand Incorporated (IPENZ).*

Mendelsohn, R. 1997. The Constructibility Review Process: A Constructor's Perspective. *Journal of Management in Engineering,* 13**,** 17-19.

Navon, R., Shapira, A. & Shechori, Y. 2000. Automated rebar constructability diagnosis. *Journal of construction engineering and management,* 126**,** 389-397.

Nawari, N. Standardization of structural BIM. publication in the Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering, 2011. 405-412.

Nawari, N. O. 2012. BIM standard in off-site construction. *Journal of Architectural Engineering,* 18**,** 107-113.

Nbims 2007. National Building Information Modeling Standard (Version 1- Part 1: Overview, Principles, and Methodologies). https://www.wbdg.org/pdfs/NBIMSv1_p1.pdf. National Institute of Building Sciences.

Nibs, N. I. O. B. S. 2007. "United States National Building Information Modeling Standard: Version 1-part 1 overview, principles, and methodologies".

Nielsen, A. K. & Madsen, S. 2010. *Structural modelling and analysis using BIM tools.* Aalborg University.

Nourbakhsh, M., Mydin, S. H., Zin, R. M., Zolfagharian, S., Irizarry, J. & Zahidi, M. Relative Importance of Key Performance Indicators of Construction Projects towards Buildability at Design Stage. Advanced Materials Research, 2012. Trans Tech Publ, 340-344.

O'connor, J. T. & Miller, S. J. 1994. Barriers to constructability implementation. *Journal of Performance of Constructed Facilities,* 8**,** 110-128.

O'connor, J. T., Rusch, S. E. & Schulz, M. J. 1987. Constructability concepts for engineering and procurement. *Journal of Construction Engineering and Management,* 113**,** 235-248.

Omniclass 2006. Omniclass: A strategy for classifying the built environment, introduction, and user guide. Construction Specification Institute, Arlington, VA, http://www.omniclass.org/.

Raviv, G., Shapira, A. & Sacks, R. Relationships between Methods for Constructability Analysis during Design and Constructability Failures in Projects. Construction

Research Congress 2012: Construction Challenges in a Flat World, 2012. ASCE, 515-524.

Rodrigo Mora, Hugues Rivard, Roland Juchmes & Leclercq, P. 2006. From architectural sketches to feasible structural systems. *In:* SPRINGER (ed.) *in Design Computing and Cognition'06.*

Ruby, D. I. 2008. Constructability of Structural Steel Buildings. American Institute of Steel Construction (AISC).

Russell, J. S., Gugel, J. G. & Radtke., M. W. 1992. Benefits and Costs of Constructability: Four Case Studies. Construction Industry Institute.

Saaty, R. W. 1987. The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling,* 9**,** 161-176.

Saaty, T. L. 1980. The analytic hierarchy process: planning, priority setting, resources allocation. *New York: McGraw*.

Saaty, T. L. 2000. *Fundamentals of decision making and priority theory with the analytic hierarchy process*, Rws Publications.

Saaty, T. L. 2008. Decision making with the analytic hierarchy process. *International journal of services sciences,* 1**,** 83-98.

Shen, Q., Lo, K.-K. & Wang, Q. 1998. Priority setting in maintenance management: a modified multi-attribute approach using analytic hierarchy process. *Construction Management & Economics,* 16**,** 693-702.

Shih, T.-H. & Fan, X. 2009. Comparing response rates in e-mail and paper surveys: A meta-analysis. *Educational Research Review,* 4**,** 26-40.

Skibniewski, M. J. & Chao, L.-C. 1992. Evaluation of advanced construction technology with AHP method. *Journal of Construction Engineering and Management,* 118**,** 577-593.

Soemardi, B. W. 2000. Virtual Reality(VR) for Precast Concrete Constructability Analysis. *Computing in Civil and Building Engineering***,** 302-308.

Suhr, D. D. 2006. Exploratory or Confirmatory Factor Analysis? . *Cary: SAS Institute*.

Sulankivi, K., Tauriainen, M. & Kiviniemi, M. Safety aspect in constructability analysis with BIM. CIB W099 International Conference Achieving Sustainable Construction Health and Safety, Lund, Sweden, 2–3 June 2014., 2014.

Surya Bakti, E., Zaimi Bin Abdul Majid, M., Muhamad Zin, R. & Trigunarsyah, B. 2011. Constructability improvement in seawater intake structure. *Engineering, Construction and Architectural Management,* 18**,** 595-608.

Tatum, C. B. 1987. Improving constructibility during conceptual planning. *Journal of Construction Engineering and Management,* 113**,** 191-207.

Tauriainen, M., Mero, A. K., Lemström, A., Puttonen, J. & Saari, A. The development of constructability using BIM as an intensifying technology. eWork and eBusiness in Architecture, Engineering and Construction. Proceedings of the European Conference on Product and Process Modeling, 2012.

Tauriainen, M., Puttonen, J., Saari, A., Laakso, P. & Forsblom, K. 2014. The assessment of constructability: BIM cases. *eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2014***,** 55.

Ugwu, O., Anumba, C. & Thorpe, A. 2004. The development of cognitive models for constructability assessment in steel frame structures. *Advances in Engineering Software,* 35**,** 191-203.

Uhlik, F. T. & Lores, G. V. 1998. Assessment of constructability practices among general contractors. *Journal of Architectural Engineering,* 4**,** 113-123.

Venugopal, M. 2011. *Formal Specification of Industry Foundation Class Concepts Using Engineering Ontologies.* Georgia Institute of Technology.

Venugopal, M., Eastman, C. M., Sacks, R. & Teizer, J. 2012. Semantics of model views for information exchanges using the industry foundation class schema. *Advanced Engineering Informatics,* 26**,** 411-428.

Williams, B., Brown, T. & Onsman, A. 2012. Exploratory factor analysis: A five-step guide for novices. *Australasian Journal of Paramedicine,* 8**,** 1.

Windapo, A. O. & Ogunsanmi, O. E. 2014. Evaluation of the barriers to the use of appropriate constructability practices on construction projects. *Journal of Construction Project Management and Innovation,* 4**,** 734-754.

Wong, W.-H. 2007. *Developing and implementing an empirical system for scoring buildability of designs in the Hong Kong construction industry.* The Hong Kong Polytechnic University.

Zolfagharian, S. & Eastman, C. 2015. Processes and Challenges to Develop Precast Concrete Test Cases for the National BIM Standard (NBIMS). *32rd International CIB W78 Conference.* Eindhoven, The Netherlands.: http://itc.scix.net/data/works/att/w78-2015-paper-087.pdf.